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POSITIONING SYSTEMS FOR UNDERGROUND TUNNEL ENVIRONMENTS

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ABSTRACT

In the last years the world has witnessed a remarkable change in the computing concept by entering the mobile era. Incredibly powerful smartphones have proliferated at stunning pace and tablet computers are capable of running demanding applications and meet new business requirements. Being wireless, localization has become crucial not only to serve individuals but also help companies in industrial and safety processes. In the context of the Radiation Protection group at CERN, automatic localization, besides allowing to find people, would help improving the radiation surveys performed regularly along the accelerator tunnels.

The research presented in this thesis attempts to answer questions relatively to the viability of localization in a harsh conditions tunnel: “Is localization in a very long tunnel possible, meeting its restrictions and without incurring prohibitive costs and infrastructure?”, “Can one achieve meter-level accuracy with GSM deployed over *leaky-feeder*?”, “Is it possible to prototype a localization system without a team of hardware engineers?”. To help answering those questions, in the first place, a comprehensive characterization of the power profile in the LHC tunnel was performed for both GSM and WLAN networks, which were transmitted over leaky-feeder cable. Subsequently, several RSSI fingerprinting methods were explored. During the characterization of the power profile, it was noticeable that GSM suffered low attenuation as it propagated in the leaky feeder, at the same time it exhibited significant changes in a short scale and among measurement sessions. Such findings motivated the research of new variants of KNN better suited for leaky-feeder, as well as fusion techniques taking WLAN network in addition. It was found that, even though KNN variants could bring interesting improvements, up to 27%, much more significant gains were attained when considering signals from the WLAN as they exhibited higher attenuation, enabling for 30 meters accuracy in 91% of the cases.

To further improve accuracy to the envisaged levels, time-of-flight techniques in narrowband were investigated. A complementary positioning system based on phase delay and aided by synchronization units is proposed and several tests are implemented using Software Defined Radio. Despite the limitations of SDR in achieving phase stability, a method following a round-trip design was shown to correctly stabilize and precisely detect small displacements.

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RESUMO

Nos últimos anos o mundo assistiu a uma profunda alteração da computação, com a entrada na era mobile. Os smartphones têm proliferado rapidamente e cada vez mais os tablet computers são capazes de correr aplicações exigentes, suportando novas atividades empresariais. Sendo wireless, determinar a localização tornou-se, não só útil para pessoas individuais, mas altamente importante em processos e segurança industriais. No grupo de Radioprotecção do CERN, localização, além de permitir encontrar pessoas, poderá ajudar a automatizar as atividades de levantamento dos níveis de radiação realizados regularmente nos túneis dos aceleradores.

A investigação levada a cabo nesta tese procura responder a questões relacionadas com a viabilidade de localização num túnel inóspito: “Será possível ter localização em túneis longos, respeitando as suas restrições e sem incorrer custos e infraestruturas proibitivos?”, “Será possível atingir acuidade na ordem de um metro com GSM propagado em *leaky-feeder*?”, “Poderemos criar um protótipo de localização sem uma equipa de hardware?” Para responder a tais questões, em primeiro lugar, procedeu-se à caracterização pormenorizada dos níveis de sinal GSM e WLAN no túnel do LHC. Seguidamente vários métodos de localização, baseados em RSSI *fingerprinting*, foram explorados. Durante a caracterização dos níveis de sinal verificou-se que a atenuação da rede GSM, ao propagar no cabo, era reduzida e, adicionalmente, a potência do sinal variava consideravelmente em pequena escala e entre as várias sessões de medida. Tal constatação motivou a investigação de novas variantes do método KNN, melhor adaptadas a cabos radiantes e que pudessem considerar vários sinais, especialmente WLAN. Os novos métodos conseguem melhorias até 27% mas, no entanto, ganhos muito mais significativos de acuidade encontram-se quando se considera WLAN, que revelando maior atenuação, chega a 30 metros em 91% casos.

Para se atingir os níveis de acuidade originalmente desejáveis, técnicas time-of-flight em narrowband foram investigadas. É desenvolvido um sistema complementar de posicionamento baseado em medidas de atraso de fase com unidades de sincronização, o qual é implementado em Software-Defined-Radio. Não obstante a dificuldade do sistema estabilizar, um novo método baseado em round-trip estabiliza e deteta pequenos deslocamentos com elevada precisão.

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ACRONYMS

AAL	Ambient Assisted Living
A-GPS	Assisted-GPS
AoA	Angle of Arrival
AP	Access Point
AWGN	Additive White Gaussian Noise
BS, BTS	Base Transceiver Station
CDMA	Code-Division Multiple Access
CERN	European Organization for Nuclear Research
FCC	Federal Communications Commission
FSPL	Free-Space Path Loss
GLONASS	Global Navigation Satellite System (Russian system)
GIS	Geo-Information Systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
ISM	Industrial, Scientific and Medical (reserved frequency bands)
KF	Kalman Filter
KNN	K-Nearest Neighbors
MAC	Medium Access Control
MIMO	Multiple-Input Multiple Output
MS	Mobile Station
LAN	Local Area Network
LBS	Location-Based Services

LCX	Leaky Coaxial Cable
LHC	Large Hadron Collider (CERN experiment)
LoS	Line-of-Sight
MS	Mobile Station
pdf	Probability density function
PLL	Phase-Locked Loop
PPS	Precise Positioning System
PS	Proton Synchrotron (CERN experiment)
RF	Radio Frequency
RFID	Radio Frequency Identification
RP	Radiation Protection
RSSI	Received Signal Strength Indicator
RTof	Round-Trip Time of Flight
SDR	Software Defined Radio
SNR	Signal-Noise Ratio
TDMA	Time-Division Multiple Access.
TDoA	Time-difference of Arrival
ToA	Time of Arrival
ToF	Time of Flight
TTA	Through-the-air
TTE	Through-the-earth
TTW	Through-the-wire
UWB	Ultra-Wideband
[V/U/E]HF	[Very/Ultra/Extremely] High Frequency
VOR	Very high frequency Omnidirectional Ranging
WLAN	Wireless LAN
WMN	Wireless Mesh Networks

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INTRODUCTION

Localization systems have become quite popular in recent years. Nowadays they play a central role in people's daily life, as well as they are a key element in many military and industrial contexts, including process control, logistics management, or safety systems.

1.1 CONTEXT

Estimating the location of mobile radios has its origins back in the beginning of the XX century, with the first Radar applications in 1904 and then during World War II to locate air, ground and sea targets. Two decades later the U.S. Department of Defense initiated the development of the Global Positioning System (GPS) – with the aim of providing reliable location and time information anywhere on earth and at low altitude. After the liberalization of the Precise Positioning Service (PPS) (US Naval Observatory, 2000) to civil use in 2000, allowing for accuracy levels better than 10 meters, GPS receivers proliferated worldwide for a myriad of applications. Currently nearly 1 billion people use the system.

GPS remains a prime example of positioning systems providing relatively high accuracy at a reasonable cost for the user. However, its accuracy is known to be very dependent on the atmospheric conditions and its use is very limited in indoor or dense urban environments. Although there have been attempts to make GPS usable in these environment, like the Assisted GPS (A-GPS), they generally fail to capture all the requirements of the desired applications.

In the context of CERN's (the European Organization for Nuclear Research) activities, GPS is used at the surface, being an integral component of general safety plans as well as geo-information systems (GIS). Although GPS is not directly applicable underground, automatic localization in such environments would also be highly advantageous for many applications of the various different technical departments at CERN. On the one hand, it would enable the tracking

of people, which would not only allow for optimized rescue plans for safety teams but also real-time monitoring of material transportation, guidance for underground work interventions, etc. On the other hand, achieving higher accuracy than common GPS implementations would be desirable as well. Of particular interest would be the application to the frequent radiation surveys carried out through the entire accelerator complex by the radiation protection group. It involves radiation measurements in thousands of points around the accelerator facilities, for which an accurate position tag is required. In this context, the correct auto-determination of the position would allow for a much faster or even unmanned characterization and documentation process – a remarkable advantage in terms of efficiency, reliability and as a consequence also personnel safety.

Within the context of this thesis, we investigate the hypothesis that, taking advantage of several different technologies, it is possible to design a positioning system, that is not only able to localize people within regions of a few meters long, but could also provide position tags with accuracy in the order of 1 meter for machine elements in the entire accelerator tunnel.

1.2 MOTIVATION

1.2.1 CERN AND THE LARGE HADRON COLLIDER (LHC) TUNNELS

CERN is the world's largest particle research laboratory and it sits on the Franco-Swiss border close to Geneva (CERN, 2014). The name comes from the french acronym for “Conseil Européen pour la Recherche Nucléaire”, a body formed with the purpose of establishing a world-class fundamental physics research organization for studying the basic constituents of matter. In 1954 the organization is founded, with 12 countries signing the convention, a list which at the moment counts 21 member states. According to the convention there are four key values, which are still valid today: Research, Technology, Collaboration and Education. And certainly these values have been a key point for success stories, even in other domains than physics.

At CERN, particles like protons and electrons have been accelerated to nearly the speed of the light and then they are made to collide so that new particles are created and observed with the aid of detectors. Numerous important, perhaps revolutionary discoveries have been made, some of which have even been awarded a Nobel Prize. Among them, in 1979 Glashow Salam and

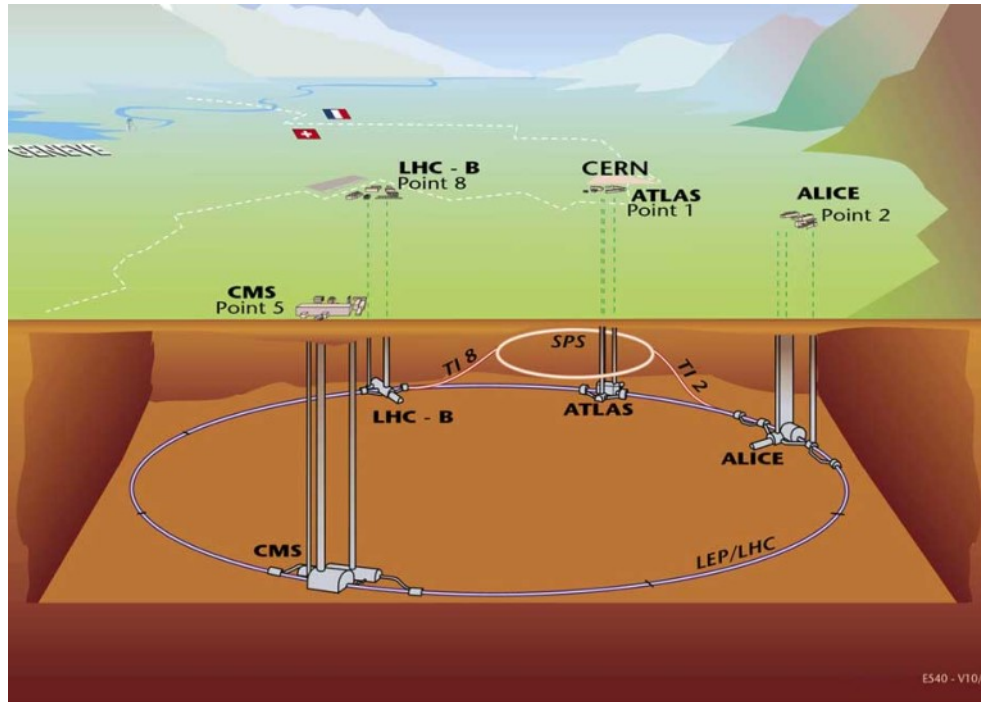


Figure 1 - A geographical view of the LHC and its four detectors

Weinberg for their theory which unified electromagnetism and the weak interactions, in 1983 Carlo Rubbia and Simon van der Meer for the discovery of W and Z particles and recently, in 2013 François Englert and Peter W. Higgs for the theory how particles acquire mass by the Higgs boson.

In order to accelerate particles, very complex machines – so called accelerators – have been developed since the early days of CERN, and they have been continuously updated and extended, creating CERN’s accelerator chain. Depending on the experiment, particles might be extracted at early stages of the chain, or proceed to next stages where they are further accelerated - see Figure 1. Particles travelling the whole accelerator chain are injected from the linear accelerator (LINAC2 - 1978) into the PS Booster (PSB - 1972), then the Proton Synchrotron (PS - 1959), followed by the Super Proton Synchrotron (SPS - 1976) before finally reaching the recent Large Hadron Collider (LHC-2008) (CERN, 2008). The LHC is a massive 27 km long ring accelerator, installed 100 m below the surface, which accelerates protons to 99.9999991% of the speed of the light in two opposite directions. Along its trajectory there are four main experiments which record and analyze the particle collisions, searching for phenomena that occur only when such high levels of energy are available.

The LHC tunnel is divided into 8 octants or, alternatively, as 8 sectors, each one with a specific purpose. Although it seems to follow a perfectly circular trajectory, the LHC tunnel’



Figure 2 – Radiation surveys
(a) A typical bending section of the LHC, (b) two radiation measurement devices

sections can either be completely straight or slightly bending. Except in very specific points, like the experiment caverns, the LHC tunnel is an arched tunnel with a typical cross section of 2.2 m radius. Furthermore, the tunnel is by far not empty, as it was conceived to hold the LHC machine itself and many auxiliary support facilities, including the massive cryogenics system and a considerable amount of cabling and electronics.

1.2.2 RADIATION SURVEYS AT CERN

In the context of a nuclear research organization, there are a number of challenges regarding radiation protection. Therefore, a dedicated group was established - Radiation Protection [12] (RP) - with the objective to assess the hazards connected with radiation and radioactivity, to ensure human safety on-site and assist all those working at CERN in protecting themselves from such hazards [13]. To accomplish this objective the group carries out several activities, already from the design phase of an accelerator and continuously during its whole life-cycle. Among them, it is this group's responsibility to:

- Advise in the operation of current accelerators and design of new ones;
- Design shielding of workplaces, mitigating effects of beam losses;
- Estimate and monitor induced radioactivity both in equipment, air and water.

Among the tasks required to fulfill their objectives, the radiation protection group has to frequently carry out radiation surveys of CERN's entire accelerator complex to assess the radiological state of the machine itself. These surveys are very important for the safety of



Figure 3 - An overview of the Radiation logging project

personnel as they ensure that any area of the tunnel is radiologically safe before access is granted. In its basic form, the radiation survey teams, equipped with probes, measure the radiation levels at specific points along the whole accelerator (see Figure 2). They record these values to evaluate the risk a certain area presents and take the necessary actions.

1.2.3 THE RADIATION LOGGING PROJECT

Radiation surveys are a critical process for the CERN RP group. However, since several measurements have to be taken every 100 m for nearly 30 km of tunnels, it represents a notorious effort in terms of time and resources. Furthermore, as the collected information was previously written to paper forms, further processing of this information required third party teams to look up the data and feed it into their own software utilities. Besides slow, this process was naturally cumbersome and highly error-prone. Additionally, given the amount of data, processing and statistical analysis was rather limited beforehand.

To address these issues, the RP group has launched the Radiation Logging project with the goal to design and implement a logging system for radiation surveys, applying state-of-the-art techniques for data acquisition, transmission, storage and retrieval.

In Figure 3 an overview of the Radiation Logging project is provided. The radiation data measured by the detectors is expected to be collected to a mobile computer, eventually a tablet,

which controls the detector and ensures the validity of the data. This device must provide an interface so that a person can supervise the process. The information is then transferred to a central database while eventually replicated for reasons of safety and availability. In the end, a front-end interface provides the user with the tools to browse and create data analysis reports.

Such a system must face a large set of requirements and constraints, including:

- A freely moving device which needs to be designed and read out continuously whilst travelling by chariot or whilst being carried by a walking or cycling person;
- It should automatically record as well as transfer all data on-the-fly via a wireless network to a database;
- The integrity of this data transfer has to be ensured in the very challenging environment of several kilometers of underground tunnels while the measurement device is moving at variable speed;
- The measurements must be associated to a position which clearly identifies the place of the measurement with a minimum of human intervention;
- Data must be accessible through a user-friendly computer interface providing a geo-referenced interactive map.

These requirements lead to three main areas of research, whose outcome must, in the end, be part of a well-integrated system. These three areas comprise:

- **Positioning**, as a novel approach for localization in such unique conditions, like the LHC tunnel, must be developed and meet the stringent constraints that apply.
- **Data communication and storage**, as we must ensure the validity and high-availability of the data, even in case of system failure, yet meeting performance requirements.
- **Information technologies**, enabling for a highly informative and user-friendly retrieval of data, which must be synchronized with pre-existing systems, namely geo-localization and machinery layout databases at CERN.

The Radiation Logging project introduces a wide range of challenges from very diverse research areas, which go beyond the scope of a PhD research thesis. In the context of this thesis one focuses on localization techniques, specially designed for the existing tunnel configuration.

1.3 SCOPE OF THE THESIS

1.3.1 PROBLEM STATEMENT

In order to fulfil its goal, the project shall provide a set of positioning functionalities and consider a set of restrictions in accordance to the context. An analysis of these factors lead to the definitions of several high-level requirements. The localization solution to be developed must:

- Provide localization coverage in the whole tunnel area while being cost effective;
- Allow for accuracy levels capable of localizing multiple persons within a few tens of meters, while being simple and resilient ;
- Can optionally be upgraded in areas where higher accuracy levels are required, in the order of one meter;
- Integrate itself transparently with existing accelerator equipment and copes with tunnel regulations;
- Integrate easily with existing personnel activities and systems operations, namely the radiation surveys. Such integration shall be as transparent as possible in order to help reducing processes time so that the advantages in terms of safety are met.

For the moment this list of requirements is kept intentionally simple. A pragmatic definition and identification of the requirements is given in 2.2.2 and 3.3.2 respectively.

1.3.2 PROPOSED SOLUTION

In the context of an accelerator tunnel, where the risk of hardware damage due to radiation is high and the area to be localization-enabled is long, solutions requiring little or no infrastructure changes are preferred. Therefore, the first part the study focus on localization techniques based on the Received Signal Strength Indicator (RSSI) of the existing wireless networks. Nevertheless, the existing scenario does not reflect the characteristics addressed in most studies of the localization research community, such as Wireless LAN (IEEE 802.11) in an office or shopping-mall. Instead, the area is covered with GSM network available throughout the tunnel via a set of *leaky-feeder* cables.

After the characterization of the RSSI profile, a method specifically developed for localization along the tunnel is suggested. The method relies on analysis of RSSI fingerprints collected all along the tunnel which are stored in a smart *radio-map*, and uses a variant of a k-Nearest-Neighbors (KNN) algorithm to obtain the position within an acceptable range for safety purposes, in the order of 50 m.

In order to further increase the accuracy, a second-stage method is proposed, which allows to improve the accuracy from regions achieved by the RSSI method to sub-meter range. This second-stage method is based on phase delay measurements of a VHF carrier injected in the leaky-feeder and subsequent translation into a position in the given range.

1.3.3 ORIGINAL CONTRIBUTIONS

The scientific contributions yielding from this PhD work and described in this thesis are introduced hereafter. They can be classified in two major groups:

Group 1 –Tunnel localization based on RSSI

- *Characterization of the Received Signal Strength Indicator (RSSI) profile of GSM signal propagated over Leaky-Feeder cable along a long narrow tunnel.*

To date and to our knowledge, this thesis includes the first studies characterizing the propagation of GSM and WLAN signals over leaky feeder cable in a narrow tunnel as long as 27 km. Besides found to be very sensitive to the presence of bodies, the RSSI for each channel is affected independently, according to the different propagation paths.

- *A KNN-based localization algorithm for RSSI fingerprints.*

A KNN algorithm was specifically designed to take advantage of multiple channels of the GSM network, the signal variance at each sample and the fact that some channels had propagated in opposite direction in the leaky-feeder cable. Furthermore, the algorithm was implemented so that additional network signals can be taken into account, including WLAN signals.

- *A framework for evaluation of fingerprinting localization algorithms supporting fusion strategies of data originating from different technologies.*

A software suite was developed for efficient testing of localization algorithms over a database of RSSI samples. The suite is optimized for large data sets and can take several algorithms for different data sources, combining them according to a defined fusion strategy. It also produces performance statistical indicators.

Group 2 – Enhancing localization accuracy with narrowband techniques

- *A localization algorithm for Software Defined Radios (SDR) based on carrier phase-delay measurements.*

The study shows that narrowband techniques can be successfully used for localization in short ranges, even if there are obstacles, by leveraging the existence of a leaky-feeder cable. The algorithm was specifically designed to operate on a Software-Defined-Radio platform, taking its limitations into account.

- *The design of a hybrid localization solution.*

The design of a localization system for the LHC tunnel which enhances the location accuracy whenever requested in a high-precision enabled area.

1.4 THESIS STRUCTURE

The remaining part of this document is organized as follows. Chapter 2 gives an introduction of general concepts used throughout the thesis, including wireless communications, forms of communication in tunnels and basics of distance finding used for positioning. Chapter 3 provides a thorough overview of wireless positioning techniques and presents the state of the art of solutions relevant to the current study, addressing in deeper detail those in which this work builds on. Chapter 4 characterizes the tunnel's RSSI profile from several temporal and spatial perspectives. In chapter 5 the development of the first-stage localization solution is presented, where the signal RSSI and new KNN variants are explored in single and multi-technology versions. A localization software framework implemented for the purpose is also described. Chapter 6 presents the high-accuracy localization approach based on Round-trip Time-of-Flight (RTOF); the approach is prototyped using Software-Defined-Radio (SDR) and tests regarding its feasibility in the tunnel are shown.

WIRELESS LOCALIZATION FUNDAMENTALS

The fast-paced development of wireless communications and the proliferation of mobile connected devices have driven the demand for accurate localization to very high levels. Depending on the application, different location characteristics are required and many wireless positioning technologies have to be taken into consideration. In general as higher levels are demanded in the various dimensions of localization quality, more sophisticated processing techniques are used as well as more precise measurements methods.

In the case of indoor environments, many challenging conditions and specific demands apply. As such, a thorough understanding of the transmission medium is required so that positioning technologies can be developed to specifically meet them.

2.1 THE “WIRELESS” CHANNEL

Since the ancient times of society, communication needs have always been among the top priorities of society and, as a consequence, communication technology has been marked by an impressive evolution and constant revolutions in its history. First wireless networks transmitted information over line-of-sight (LOS) distances using smoke signals, and semaphore signs. The invention of the telegraph, by Morse in 1838, and lately the telephone, by Bell in 1876, came to revolutionize these means of communication by transmitting electrical signals over a wired medium. Relatively fast communication over long distances was made possible.

This kind of transmission remained the only possibility until Marconi demonstrated the first radio transmission in 1895. At the age of 21, after some modifications to his initial prototype, he is able to communicate over a hill - a distance of 2.4 km (Marconi, 1909). Since then, the world has witnessed one of the most impressive development in technology and industry success. Cellular systems have experienced exponential growth over the last decade and there are

currently around two billion users worldwide. Indeed, cellular phones have become a critical business tool and part of peoples' everyday life.

2.1.1 RADIO PROPAGATION

Wireless networks differ fundamentally from wired networks due to the unpredictable and difficult nature of the wireless channel. As it propagates, the signal power varies as a function of space, frequency and time. Besides attenuation (also known as Large-scale fading, or *Slow-fading*), the particular conditions of the propagation path might favor reflection, refraction and scattering effects so that even minor movements of the transmitter, receiver or surrounding objects may considerably affect the transmission quality. *Diffraction* is the effect of “bending” the propagation path on object corners, while *Reflection* happens when the signal hits a surface with dimensions larger than its wavelength, and *Scattering* when the signal is “cut” by objects much smaller than its wavelength. For a deeper insight on these effects refer, for example, to (Parsons, 2000) and (Goldsmith, 2005).

Radio propagation models try to assess the signal power evolution as a function of distance, and usually combine empirical and analytical methods. Although analytical models are provide adequate approximations in free-space and simpler propagation scenarios, they are ineffective in estimating the power in a dense environment due to unpredictability of the effects mentioned before (Latvala, et al., 2000). In turn, empirical models can be developed very fine-grained, but their validity holds only for the same physical configuration and frequencies.

Path Loss

The fundamental estimation of the resulting signal strength of an electromagnetic wave after travelling in free space, usually air, is known as *Free-Space Path Loss* (FSPL). It assumes no obstacles and does not account for hardware imperfections. The premises for the equation are that power loss is proportional to the square of the distance between transmitter and receiver, and also proportional to the frequency of the signal.

$$PathLoss = \left(\frac{4\pi d}{\lambda} \right)^2 \quad (\text{eq. 2.1})$$

Equation yields the power attenuation coefficient, given the distance (d) and wavelength (λ) in meters. It is often practical to obtain attenuation in dB's, given the frequency in Hz and distance in km. In that case the expression becomes:

$$PathLoss_{dB} = 20 \log_{10} d + 20 \log_{10} f - 32.45 \quad (\text{eq. 2.2})$$

The path loss equations are used as a part of the Friis free-space model, which may take transmitter and receiver antennas' gain into account. This model is the basis for large-scale propagation models but is only valid in the far-field of the transmission antenna. For shorter paths, more realistic models exist, including the Hata-Okumura and the COST231-Hata models (Rappaport, 1996), both to frequencies up to 2 GHz. For higher frequencies (Erceg, et al., 1999) proposed a model which takes into consideration the type of terrain, the antenna dimensions and a shadowing factor.

Shadowing

According to the path loss model, the power at a certain distance d from the transmitter is a deterministic. However, it is known that for the same the distance point the power varies due to reflection and diffraction by interfering objects along the path. These effects are in general known as shadowing, and measurements show they can be modeled as a log-normally distributed (normal in dB) random variable, i.e.:

$$\eta_{shad_dB} \sim Norm(0, \sigma_{shad}) \quad (\text{eq. 2.3})$$

Shadowing (σ), at a distance of 100m, has typically values in the order of 6 dB.

Fast-Fading

Fast, or Small-Scale, fading is characterized by quick variations of the signal power over short distances. This effect happens when the scattered signal components interfere among each other, a mechanism known as Multipath Interference. Due to the different propagation paths, they may present different amplitudes and phases and, if the phases are considerably different, destructive addition takes place and a lower signal strength is measured. The impulse response of a channel representing the sum of all the signal scattered components can be given by:

$$h(t) = \sum_{m=1}^N A_m \delta(t - t_m) \quad (\text{eq. 2.4})$$

In (eq. 2.4) A_m is the amplitude distortion and δ the Dirac delta function delayed by t_m . In the case of sinusoidal waves complete destruction occurs if two components have a phase shift of π rad. Therefore, having approximately 3 m wavelength, 100MHz signals exhibit fast fading phenomena in the meter range.

2.1.2 A SHARED MEDIUM FOR COMMUNICATIONS AND LOCALIZATION

Many other factors arise from the fact that air is a shared medium. First of all, the radio spectrum is a scarce resource and, due to that, is controlled by regulatory bodies, both regionally and globally. Second, security is also more difficult to implement since anybody can “listen” to any communication in-range. Wireless networking is also significantly more challenging. Cellular networks must be able to locate a given user wherever he is among billions of globally-distributed mobile terminals and ensure transmission is kept possible even when the receiver is moving fast and eventually traverses areas covered by different transmitters.

Wireless networks for communication

Cellular network systems were those which pushed for wireless revolution. Their main purpose was to provide national and international coverage for bi-directional voice and data communication. It is named after the network coverage layout, in which the Base Stations cover a relatively small area, called cell, and several adjacent cells are required to properly cover a geographical area. In this configuration frequencies can be reused in non-adjacent cells, leading to better efficiency in spectrum use. While in first generation cellular systems (1G) communication was analogue, second (2G) and third generation (3G) use digital transmission, employing TDMA and CDMA multiplexing techniques.

Apart from the wide coverage of wireless networks and highly motivated by the advent of fast Internet, the demand of limited-range high-speed wireless networks has steadily increased. Wireless LANs started to appear in the early 1990's with data-rates on the order of 1-2 Mbit/s. They operate in the unlicensed (ISM) frequency bands and, given the transmissions' limited power, frequency allocation and regulation are no longer an issue. After the first generation of such devices being incompatible among them, a set of standards have been

developed by the IEEE consortium, which have been adopted worldwide. In the first WLAN standard, the IEEE 802.11 (IEEE, 1997), systems were specified with data rates up to 2 Mbit/s and a range of approximately 150 m. The current standard IEEE802.11n (IEEE, 2009) specifies data rates up to 600 Mbit/s by employing Multiple-Input Multiple-Output (MIMO) techniques, considerable larger bandwidth channels (40 MHz), and several MAC layer optimizations.

Communication networks for positioning

Across times and technologies, wireless networks have been deployed with the main purpose of providing data communication abilities to users. They focus, in the first place, on the network characteristics perceived as quality parameters, such as data rate, range, mobility support and fairness. Nevertheless, another use of the network has becoming increasingly important. In 1996 the Federal Communications Commission in the U.S. introduced requirements for wireless service providers being able to locate users within 100 meters in an emergency situation (FCC, 1996); a similar directive was set to the European Union (EC, 2002). This concept was later extended to Wireless LANs (WLANs) and high accuracy geo-localization technologies started to be explored. These techniques can virtually turn any wireless network into a tracking system for people and goods. They are primarily relevant for cellular network providers as a mean to locate users and optimize the network performance. Nevertheless they can be used for a myriad of applications, personal or industrial, where the location of something is to be monitored or even automatically controlled.

The Global Positioning System - GPS

The most known and widely used positioning technique is that used by the GPS system (GPS.gov, 2014), based on measurements of the signal delays - see part 2.3.1. The propagation times of signals from satellites at known locations are measured simultaneously, and the distance between a satellite and a user's receiver is obtained by assessing the propagation time and assuming LOS conditions. In many cases, however, the LOS signal is followed by multipath components that arrive at the receiver with a delay, introducing significant changes into the signal travelling time its gain estimation, especially in urban environments due to the many reflections from buildings and other objects. For exactly those reasons GPS doesn't work or performs poorly in such environments.

2.2 CLASSIFICATION OF POSITIONING SYSTEMS

There are several possibilities for classifying positioning systems, each of which making use of different characteristics. Although it is common to characterize according to the infrastructure underlying technology (e.g.: WLAN, Cellular, proprietary) or the signal used (e.g.: infrared, sound, cameras), these types of classification are somewhat bound to a given domain (e.g. Indoor localization - see section 3.2 from Chapter 3). However it is important to understand its classification according to the topology, as it will define the system design.

2.2.1 CLASSIFICATION ACCORDING TO THE TOPOLOGY

In a classification according to the topology (Drane, et al., 1998), the entities Base-Station (BS) and Mobile Station (MS) are defined and they might independently play the role of “Obtaining” or “Using” the position information. In this definition is included the case they perform both (“obtain and use”) or none of them (i.e.: localization passive). In such conditions, four scenarios are possible:

- **Self-positioning:** The MS performs the signal measurements and processes them to obtain the location - Figure 4(a). Such topology is quite common since it is well-adapted for situations where positioning is not the primary goal of the network, although the MS can still profit from the signal to infer location properties (e.g.: fingerprinting over WLAN). Self-positioning is also the only viable solution for massive localization systems, where communication with a BS would either create a bottleneck or be difficult, as in the case of GPS. Self-positioning is a topology both scalable and simple, yet it has the eventual disadvantage that the network does not know the positioning of the MS's.
- **Remote positioning** (or network-based positioning): The BS is responsible for calculating the MS position based on the signal received directly or indirectly from it - Figure 4(b). This is the case of typical tracking performed by cellular networks, where all the information is generated on the network side but not available to the MS. Remote positioning systems therefore suffer from poor scalability, while allowing for higher integrity, privacy and performance from the operator point of view.
- **Indirect self-positioning:** The BS calculates the position of the MS and sends to it the location information via a data channel - Figure 4(c). This makes the location available also to the MS even when it is technologically preferable to calculate the position in the BS.

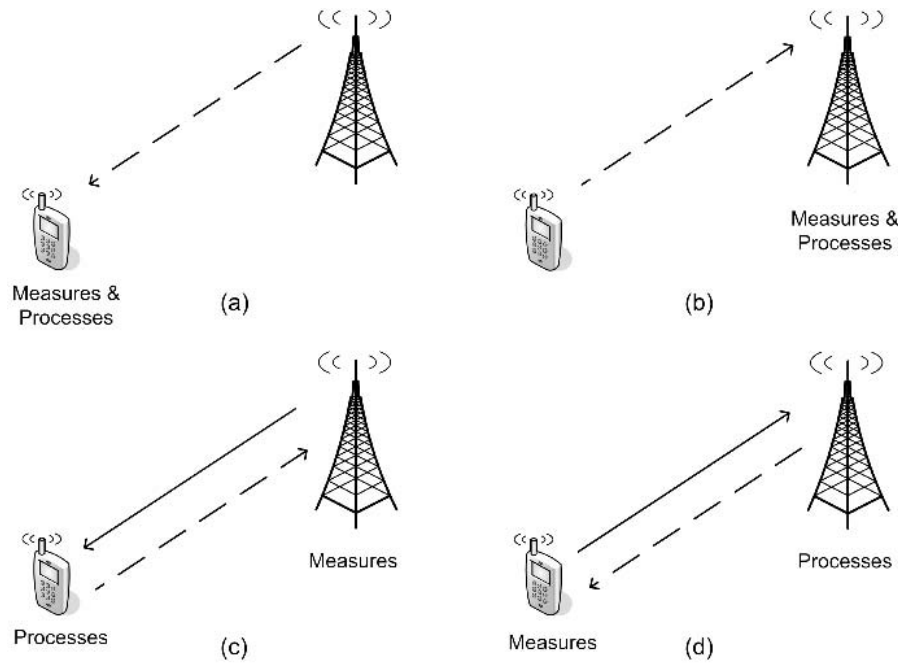


Figure 4 - Classification according to system topology.
(a) self-positioning, (b) remote positioning, (c) Indirect self-positioning, (d) Indirect remote positioning.
Dashed-lines represent actual signal being measured, while solid lines represent transfer of measurement information.

- **Indirect remote-positioning:** Similarly to the indirect self-positioning, the roles are separated but in this case they are reversed, being the MS responsible for obtaining and sending the location information to the network - Figure 4(d). This option allows for the network to track the MS, even though the BS didn't participate in the location finding.

It is also often the case that other parts of the system require location information, and therefore, independently of the design, the components might establish additional data links to exchange such information.

2.2.2 CLASSIFICATION ACCORDING TO USER REQUIREMENTS

From the user's perspective, each application will require a set of characteristics to be met before the localization system can be used for its purpose. A robot in a surgery must not have 1m location accuracy, even if it's perfect at all other aspects. Other applications might require highly available systems (24/7) while relaxing the need for accuracy, like patient tracking in hospitals. Even though accuracy is a very important factor when deciding on a technology, others,

depending on the context, might even be more important. In the end all must be taken into account with their own priority.

According to the work by Mautz (2012) there are 16 kinds of requirements, which can be perceived as 16 dimensions defining the characteristics of a system:

- **Accuracy / Uncertainty** – “Positioning accuracy” should be perceived as the degree with which an estimated position matches the true value at a given time, which is usually calculated at a confidence level of 95%. This term is being deprecated in favor of “Measurement Uncertainty”, well defined by the Joint Committee for Guides in Metrology (JCGM) in JCGM 200:2008 (2008).
- **Coverage area** – Refers to the spatial extension the system operates in, while guaranteeing specifications. Three broad classifications exist: *Local coverage*, *Scalable coverage* and *Global coverage*.
- **Cost** – Cost is always an important requirement, which for the case of positioning systems has to be assessed in several perspectives, including initial deployment, per user/device cost, extension and maintenance effort.
- **Infrastructure** – The required infrastructure will mostly impact the initial deployment effort and, if required, can be passive or active, dense or sparse, dedicated or leveraging another.
- **Market maturity** – Whether the technology is a concept, being developed or a proven product.
- **Output data** – The output might be simply a set of 1-, 2- or 3-D coordinates, but additional parameters might be useful in some situations, including velocity and uncertainty assessments.
- **Privacy** – Whether the determined positions should be available to the user itself only, a set of authorized operators, or publicly shared among all users.
- **Update rate** – Update rate can vary from the position being calculated every few days to elevated rates (e.g.: hundreds of hertz for a robot arm).
- **Interface** – Shall the system provide human-machine interfaces (e.g. a GUI) or machine interface only (e.g.: Rest API's, protocol over the network, serial).

- **System integrity** – The possibility to evaluate the quality of an estimate (output) and alert the user if the error exceeds a defined limit. This might be a critical factor for safety systems.
- **Robustness** – Relates to which degree the system can cope with harsh operating conditions and protection against misuse, theft or jamming.
- **Availability** – Encompasses the number of requests the system can process and the error frequency and recoverability, measured by requests-per-second, mean-time-between-failures and percentage of up-time.
- **Scalability** – The possibility of the system to gradually increase its availability or coverage area, which can come at additional costs or detriment of other properties (e.g.: accuracy).
- **Number of users** – Whether the system is operated by a single user (e.g. robot), supports multiple users up to infrastructure saturation, or accepts unlimited users thanks to a decentralized design (e.g.: passive sensors).
- **Intrusiveness / User acceptance** – The degree to which the system integrates the environment and is adapted to the involved processes, and can range from imperceptible to disturbing.
- **Approval** – Some systems might be subject to approval and certification both at the local level (company internal regulations) and obeying national legal regulations (e.g. electromagnetic power emission levels).

These parameters pose a multidimensional optimization problem to the system to be built. Having in mind that no system can perform exceptionally in all requirements, a careful assessment of the priorities is a key step during its design phase, which will define some of the fundamental aspects, including the technology.

2.3 WIRELESS DISTANCE MEASUREMENTS

Within the positioning domain, one can identify two concepts that are closely related: *distance measurement* and *location*. While the first aims at determining the distance between two objects, the latter deals with objects as a point in geo-referenced coordinates system.

Nevertheless, distances can help us to determine a location and, the other way round, it is possible to calculate the distance between two referenced locations. After these, other measures can further be calculated, namely velocity and acceleration. Nevertheless, one must not overlook that time dependent measures are susceptible to errors due to delays introduced in the measurement process.

Three kinds of measurements can be used to obtain distance or location information from a system using electromagnetic waves (Bensky, 2007):

- **Time-of-Flight (ToF) / Time-of-Arrival (TOA) and Time-Difference-of-Arrival (TDOA):** based on the measurement of the propagation time, absolute or relative value respectively;
- **Angle of Arrival (AoA):** based on the measurement of the propagation angle;
- **Received Signal Strength Indicator (RSSI):** based on the measurement of the signal power.

Besides these three measurements accessing the signal's electromagnetic properties, other methods permit estimating a position based on other resources:

- **Cell-ID:** based on the identification of the signal;
- **Inertial frame:** Position is calculated from linear and angular acceleration, without the aid of any infrastructure. These measurements are the foundation of the *dead-reckoning* method, used since centuries for marine navigation.
- **Pattern analysis:** Generic collection of signal samples, including image and sound, for later identification using Digital Signal Processing (DSP) software and Artificial Neural Networks (ANN).

Despite the great importance of inertial frame and pattern analysis methods, they lie outside the scope of this thesis. They nevertheless found the base to some position techniques mentioned in section 2.4.

2.3.1 TIME-OF-FLIGHT

Given that radio signals travel at the speed of the light, it is possible to estimate the distance between the emitter and receiver by measuring the time a signal takes to travel from a

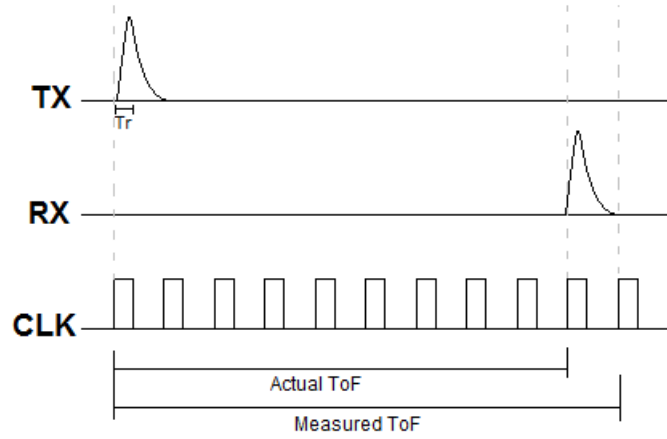


Figure 5 - Time resolution in ToF systems

point to another, i.e., transmitter to receiver. The time, t , the signal will arrive to the receiver is given by:

$$t = t_{TX} + \frac{d}{c} + dT \quad (\text{eq. 2.5})$$

In (eq. 2.5) t_{TX} is transmission time, d the distance and c the speed of light. dT is a term to stand for clock drifts, which must be considered if the send/receive devices are not completely synchronized.

A prime and well-known application of this concept is radar. Modern tracking and missile control radars use the monopulse technique (U.S. Naval Research Laboratory, 1943) in which, in its basic form, a device emits a radio frequency pulse and measures the time elapsed until the reflected pulse is acquired by the receiver device. The distance is then calculated based on the pulse's propagation speed, usually the speed of the light, and the fact that the pulse travels forth and back, i.e. double the distance between the objects. In these systems, the accuracy is proportional to its time resolution which, in turn, is proportional to clock frequency.

These concepts are illustrated in Figure 5. It is then clear that the performance of the method is better as we reduce the clock period. Even though one clock cycle might seem very little error, it might introduce significant error margins when very high accuracy is required. Suppose the case of a 10 MHz system. A single cycle (100 ns) is enough for the signal to travel 30 m and therefore the system is effectively limited to an accuracy of 15 m.

Another aspect is that the pulse width must be narrow enough to allow for an adequate detection. On the one hand we must ensure that no pulse echo is received while it is still being transmitted and, on the other hand, multiple reflections of the pulse should be distinguishable among them so that one can clearly identify the first reflection and infer the shortest path. The pulse rise time T_r depends directly on the signal bandwidth B which, for a square wave, is given by:

$$T_r = \frac{1}{B} \quad (\text{eq. 2.6})$$

The technique of measuring a reflected signal, as employed in radar, implicitly solves a commonly complex problem: the need for device synchronization. Since the transmitter and receiver devices are together they can share the clock reference and, therefore, it is straightforward to assess the correct travel time. In the case of a decoupled design, where the transmitter can't be physically connected to the receiver, a mechanism for very-precise clock synchronization must be in place. In order to avoid the synchronization problem, another technique is often explored - TDoA.

2.3.2 TIME-DIFFERENCE-OF-ARRIVAL

Several reasons can be behind a decoupled design despite the complex problem it introduces: the need for a simple receiver, a noisy and/or high-attenuation transmission medium, scalability requirements, etc. TDoA takes into consideration additional signal sources to avoid the need for absolute clocks by measuring the relative delay between signals. This process usually allows to calculate the clock drift and to synchronize the units as well.

GPS is a prime example of a TDoA systems, where all the previously mentioned conditions apply. It finds the location by solving a system of typical ToF equations contemplating a clock-drift term, requiring information from at least four satellites (Langley, 1991).

Synchronized transmitters, unknown clock-drift

When measuring distance, basic ToF accounts for unknown distances only which can therefore solved using simple motion equations. When inserting a clock-drift (dT) term, additional information must be added to the system so it can be solved.

One of the most popular techniques is to install an additional transmitter, which is synchronized to the first unit. Both units then transmit signals, either simultaneously or with known delay among them, so that the receiver is able to determine the propagation times and even to correct its clock drift.

Consider the situation where the distance between a BS and a MS is to be calculated. With the aid of a second transmitter in line¹, if both send a synchronized pulse, the time at the receiver shall respect a system of equations based on (eq. 2.5)¹:

$$\begin{cases} t_1 = t_{TX1} + \frac{d1}{c} + dT \\ t_2 = t_{TX2} + \frac{d2}{c} + dT \end{cases} \quad (\text{eq. 2.7})$$

Since dT depends on the receiver, $t_{TX2} = t_{TX1} + K$ where K constant, and defining $\Delta t = t_1 - t_2$, one obtains:

$$\Delta T = \frac{d1}{c} - \frac{d2}{c} - K \quad (\text{eq. 2.8})$$

Finally, being an infrastructure, the distance between the transmitters is known. Therefore $D = d1 + d2$ ¹, yielding the solutions:

$$\Delta T = \frac{2 \cdot d1 - D}{c} - K \Rightarrow \begin{cases} d1 = \frac{D + c \cdot (\Delta T + K)}{2} \\ dT = t_1 - t_{TX1} + \frac{d1}{c} \end{cases} \quad (\text{eq. 2.9})$$

As seen in (eq. 2.9), the distances can be calculated based on the measured ΔT and system known constants. For clock synchronization to be possible the only condition would be to calculate dT by having access to t_{TX1} . This could be accomplished by encoding t_{TX1} and transmitting it in the signal itself. Clock synchronization is also performed in GPS and indeed most receivers automatically set their date/time based on the network. For higher dimensions, in 2- and 3-D spaces, the process is called Multilateration, and is described in section 2.4.2.

¹ The case of 1D requires transmitters is opposite sides of the receiver. For higher dimensions see 2.4.2

2.3.3 ANGLE OF ARRIVAL

AoA can only be used in systems employing directional or sector antennas. It takes advantage of the angular information provided by the antennas and, using triangulation techniques, the location can be determined as the intersection of the reconstructed transmission paths. The Angle-of-Arrival approach has long been used for distance and location purposes. They have been of particular interest for broadcast networks in order to locate illegal transmitters and eavesdroppers, as well as for tracking via tiny transmitters in the target (Bensky, 2007).

Besides its relative simplicity, this approach offers diverse advantages which make it preferred over the other approaches. In general, no cooperation is required from the target, it can be used in a wide frequency range – from HF to EHF – and is also appropriate for long distances. Location and distance can be estimated using exclusively AoA methods via triangulation techniques, the only requirement being, at least, two directional antennas. The accuracy of the method is then intrinsically related to the directional performance of the antennas. The *directivity* of an antenna is a theoretical concept depending on its construction and geometry and is of major importance for AoA direction-finding methods. It is calculated as the ratio of the power density at a given distance and location against the average power density in all directions at that distance. This measure is often conveniently displayed using *Antenna Directivity Pattern* graphs, like the one shown on Figure 6.

There are several approaches to estimate the AoA. In single antenna systems, a simple approach is that a receiver rotates the antenna until it finds the angle where the RSSI is maximum.

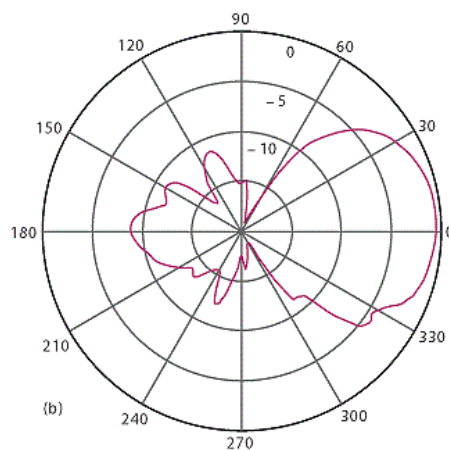


Figure 6 - A directional antenna directivity pattern

Nevertheless its performance can be severely affected due to ambiguities resulting from lower signal-to-noise ratios. If an array of antennas is available, significantly higher directional precision can be obtained by comparing the amplitudes and/or the phases (phase interferometer) from the individual antennas.

2.3.4 RECEIVED SIGNAL STRENGTH INDICATOR (RSSI)

The RSSI is a measure of the magnitude of the signal power as assessed by the terminals of a receiver. This measure can then be used to obtain an estimate of the position, by using analytical and/or empirical models (see section 2.1.1). Considering the *Path Loss Propagation Model*, since the received signal's strength decreases as the distance to the transmitter increases, one can estimate the distance (and vice-versa). Simple triangulation can then be employed to determine the position. RSSI-based methods have several advantages when compared to approaches based on other measurements. In the first place they require little or no changes to the network infrastructure: terminals are only required to read the RSSI and to process it in software. Second, there is no need for devices synchronization or cooperation, as the RSSI shall be time-independent. Also, the method works independently of the signal modulations or data rates. Methods based in the RSSI have, nevertheless, problems regarding the signal stability which severely limits the accuracy. Due to the permanent environmental changes affecting the propagation conditions, interferences and effects of multipath, scattering and reflections, the RSSI at a receiver is generally subject to significant fluctuations (Bensky, 2007). Especially when no direct line-of-sight is available, these effects can cause severe degradation of the signal

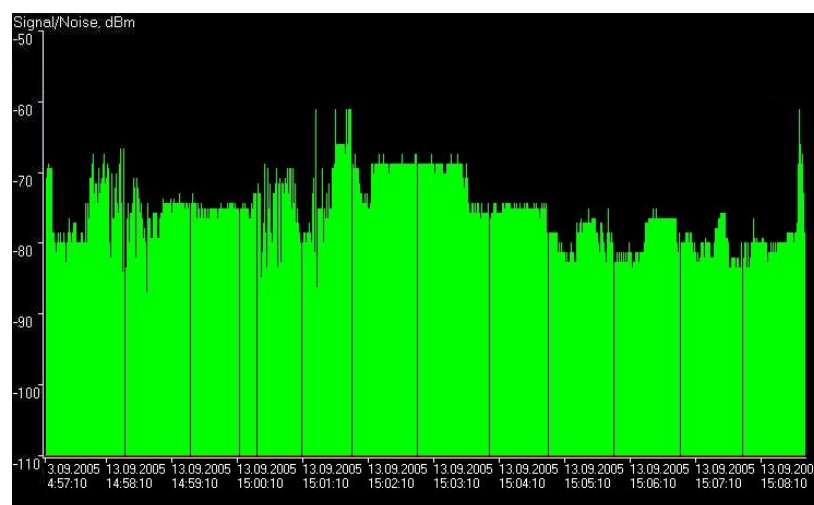


Figure 7 - Evolution of the RSSI in a WLAN network.
In green is shown the RSSI in dBm, captured by NetStumbler.

stability with notorious implications on the positioning accuracy. Figure 7 shows the RSSI in dBm for a WLAN network. Notice that fluctuations are as high as 20dB, i.e., a factor of 100.

Analytical and empirical approaches

Two main approaches are used for the estimation: analytical or empirical. Analytical approaches make use of the radio propagation models. Therefore obtaining the position becomes as simple as solving the loss equations in respect to the distance and inputting the measured power. The *Free Space Model* (eq. 2.1) is definitely a reference for such estimation, in the form that it is used to calculate a constant component, which depends on the distance. To account for this stochastic behavior of the received power as shown before, the most generic approach is then to consider all these effects as single additive Gaussian-distributed components with a given standard deviation σ_{shad} , as:

$$RSSI = p_0 - 10\beta \log d + n_{shad}, \quad n_{shad} \sim \text{Norm}(0, \sigma_{shad}) \quad (\text{eq. 2.10})$$

In (eq. 2.10) it is given that the RSSI directly depends on the transmitted power p_0 subtracted a path loss component with distance d and loss exponent β , and a random loss n_{shad} . Other models try to express the propagation characteristics of more elaborate environments, including indoor locations. Despite their simplicity, these methods can indeed work well as long as they accurately reflect the real propagation conditions. This situation is, unfortunately, very hardly the case of indoor scenarios, where a large shadowing component has generally to be introduced, which is a direct source of distance error. Analytical approaches remain, therefore, an option almost exclusive to outdoors and other simple environments, where line-of-sight is available with little multipath and reflection conditions.

For applications, including positioning, requiring an accurate characterization of the signal strength in a complex space, empirical approaches have been explored. A possibility is to measure the signal strength at a set of predefined locations to create *a map* of the network, which can be later tested for similarities with new samples. These techniques are denominated of *Fingerprinting*, and are described in more detail in section 2.5.

2.4 POSITION FINDING TECHNIQUES

Positioning is typically performed by processing several measurements, as described in the previous section, and often, on a combination of some of them. In this section we provide an overview of the basic positioning techniques, including proximity and multilateration methods, as well as some extended information on Fingerprinting.

2.4.1 PROXIMITY SENSING

Amongst the simplest location finding principles, proximity sensing does not require the measurement of signal between the parties. Instead, it is based on the identification of the signal which, in cellular-style networks, translates into a certain location region defined by the network coverage.

Proximity methods in cellular GSM networks

Cellular networks have been intrinsically able to localize terminals with this method by using the *Cell-ID*, more specifically, the GSM channel identification.

Even though they are generally straightforward, due to the large area covered by a single network cell, especially in rural areas – up to 30 km, the positioning error can also be very significant. To improve this figures a variant of the method, known as *virtual center*, calculates the position as the central point among all the detected cells' positions (Cheng, et al., 2005) which can optionally be inversely averaged by their radii:

$$X = \frac{\sum_{i=1}^N \frac{1}{r_i} X_i}{\sum_{i=1}^N \frac{1}{r_i}} \quad (\text{eq. 2.11})$$

In a project involving localization of mobile units for assessing road traffic in Duisburg, Germany (Jung, et al., 2009), by approximately calculating the cell's geometry by identifying the signal from adjacent BTS and using the antennas' directional capabilities, an accuracy better than 477 m was found for 67% of the cases.

Without further analysis of the signal characteristics, as seen in the next part, little further optimization can be done. Nevertheless this method finds its usefulness mostly for networks where, the cell size is natural or intentionally kept small. This can be the case of micro- (radius:

200-2000 m), pico GSM cells (radius: 4-200 m) (Linnartz, 1993), or dense coverage with other networks.

Proximity methods in other networks - RFID

Despite the wide application of this method to cellular networks, these methods have been explored for other standardized networks, including Bluetooth (standardized as IEEE 802.15), WLAN (IEEE 802.11) and proprietary systems. The basic principle is always applicable: localization is defined to be that of the cell(s) in range. For a finer accuracy other signal properties are used for sub-cell localization, mainly power and direction.

Due to its relatively low cost, and eventually making use of passive elements, a very dense network of RFID tags could enable localization with good accuracy levels (relative to the network density) in situations where GPS is not enough or not even available, like tunnels, indoors and dense urban areas. An experiment by (Chon, et al., 2004) shows that information from RFID tags combined with GPS and gyroscopes allow for accurate localization of vehicles in roads, even when they are moving over 100 km/h. See section 3.5.1 for more details.

2.4.2 MULTILATERATION

The basic mechanisms to determine the location either use distances, angles or a combination of both. In some cases, distances and angles can only be given in relative values, but the ambiguity can be resolved with the help of additional sources of information.

Trilateration

Trilateration is a geometric process which determines positions from regions defined by one or more circles. In terms of positions, a distance value only represents the radius of a circumference where the receiver might be located. If one additionally knows the distance to a second reference point, the intersection points of the circumferences might be calculated and we end up with two single possible positions, as exemplified in Figure 8.

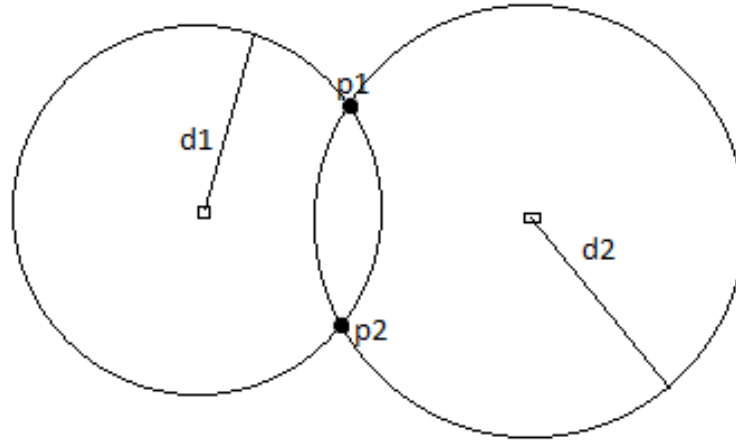


Figure 8 - Possible locations after the intersection of two distance' circumferences

In 3-D spaces, the radius define spherical surfaces, whose intersections form rings. Even if altitude can be known, two positions are still available. Without additional information, and due to uncertainties in the radius' measurements, the whole intersection region has to be taken as a location, which might imply a large error. Therefore, at least a third reference point is required to solve this ambiguity and improve the accuracy.

The trilateration principle assumes that the distance to the transmitters can be accurately determined by the mobile unit. In some cases, however, because synchronization among transmitters and receivers might be unfeasible or difficult, such assumption can't be made. Among others, the GPS system solves this limitation by using extra sources of information, satellites in its case, and in the base of its mathematics there is a 3-D version of the TDoA equation (eq. 2.7):

$$T_r \begin{cases} t_1 \cdot c = \sqrt{(X - x_1)^2 + (Y - y_1)^2 + (Z - z_1)^2} - c \cdot dT \\ t_2 \cdot c = \sqrt{(X - x_2)^2 + (Y - y_2)^2 + (Z - z_2)^2} - c \cdot dT \\ t_3 \cdot c = \sqrt{(X - x_3)^2 + (Y - y_3)^2 + (Z - z_3)^2} - c \cdot dT \\ t_4 \cdot c = \sqrt{(X - x_4)^2 + (Y - y_4)^2 + (Z - z_4)^2} - c \cdot dT \end{cases} \quad (\text{eq. 2.12})$$

In (eq. 2.12) the left-hand side of the equations (t_1, t_2, t_3, t_4) represent the flight time as measured by the receiver, (x,y,z) the coordinates of each satellite, and (X,Y,Z) and dT the unknown receiver's coordinates and clock drift respectively. The four unknown parameters can then be calculated by resolving the system of the four distance equations. Due to the squares and square-roots in the equations, the system cannot be solved linearly. Therefore a procedure called

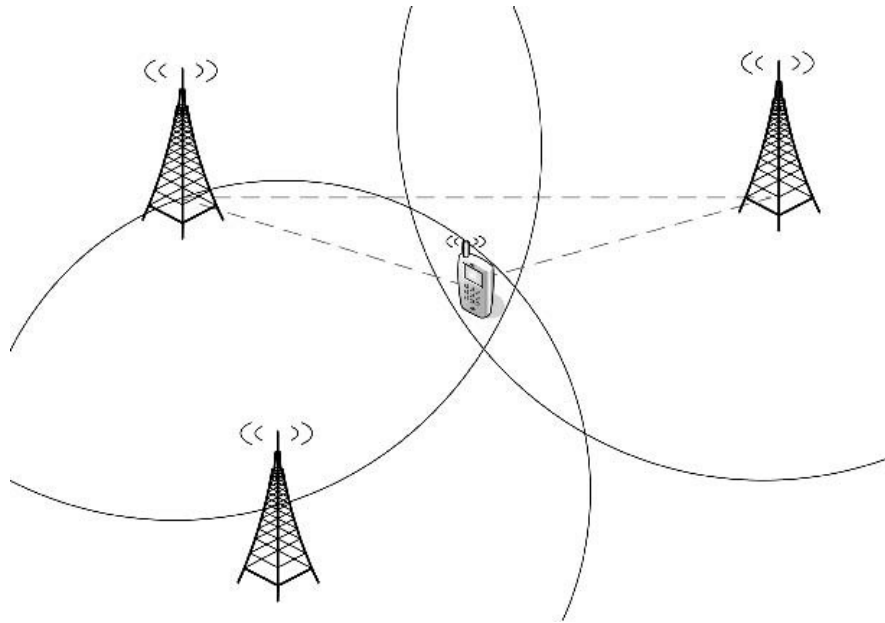


Figure 9 - Trilateration principle for localization of a Mobile Station

Newton-Raphson iteration is used, which expands the equations into linear approximations so that they can be solved simultaneously (Langley, 1991). The process is iterated several times until the yielded correction increments are within an acceptable range.

However, between 24 and 32 satellites continuously orbit the Earth (GPS joint program office, 2004) and frequency many of them become available to a receiver when calculating the position. In order to overcome the excess of information problem, instead of discarding “less-interesting” signals, all signals are taken into account and the final position is the best fit to all partial solutions, calculated using the *least-squares* method (Langley, 1991).

Triangulation

With Angle-of-Arrival information, the location can be calculated using two directional antennas as the intersection of the transmission directions. This geometric procedure is known as *Triangulation* – see Figure 10.

If the coordinates of both receivers (R1, R2) are known, there is a single point P1 found through triangulation. Assuming a small directional error margin, it is also easy to understand that the performance of this method depends on the relative distance of the target to the reference points.

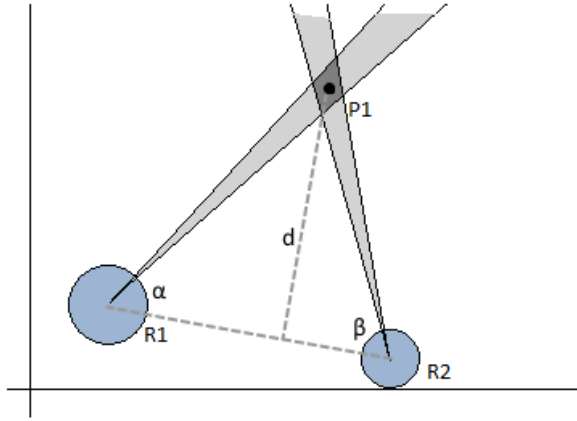


Figure 10 - Estimating location via the intersection of AoA information

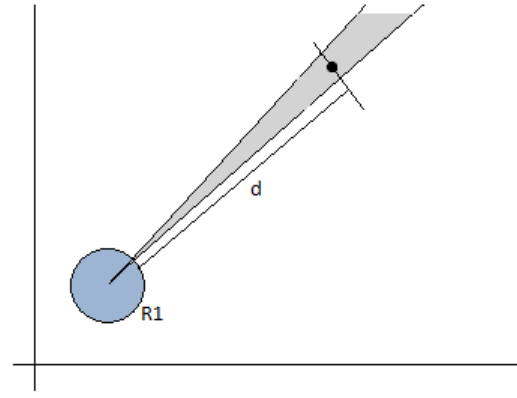


Figure 11 - Location finding using Angular and distance information

Based on the principles of Euclidean geometry, distance d can be calculated from the trigonometric relations of the distance between R_1 and R_2 and the angles made with P_1 , as:

$$\overline{R_1 R_2} = \frac{d}{\tan \alpha} + \frac{d}{\tan \beta} \quad (\text{eq. 2.13})$$

Resolving to d , using the trigonometric identities $\tan(\alpha) = \sin(\alpha)/\cos(\alpha)$ and $\sin(\alpha + \beta) = \sin(\alpha) \cos(\beta) + \cos(\alpha) \sin(\beta)$, we end up with:

$$d = \overline{R_1 R_2} \frac{\sin \alpha \sin \beta}{\sin(\alpha + \beta)} \quad (\text{eq. 2.14})$$

With the distance d defined the position of P_1 can be easily calculated. In a 2-D plain, one approach is to calculate the distance $\overline{R_1 P}$ and translate α into the geographical absolute angle α_{abs} , so that the P coordinates are given by

$$P = R_1 + \overline{R_1 P} \cdot \langle \cos \alpha_{abs}, \sin \alpha_{abs} \rangle \quad (\text{eq. 2.15})$$

It is also of interest the case when both the direction and the distance are known by the receivers, therefore making (eq. 2.15) directly applicable. In such situations, since both measurements are complementary and sufficient to define a point in a referential, only one receiver is actually necessary - see Figure 11.

Nevertheless, both capabilities don't have necessarily to be in the same device. In some systems the target can actually perform one of the measurements. For instance in cellular networks, it's actually the terminal which monitors the signal strength, while the angular information and processing is performed on the base station.

Due to the simple infrastructure this system requires, it is actually used in a number of applications, including very high frequency omnidirectional ranging (VOR) navigation, wildlife tracking and article location in warehouses (Bensky, 2007).

2.4.3 DEAD-RECKONING

Dead-reckoning is a technique that calculates the current position based on the previous ones, updating it based on the information coming from different sensors, namely speedometers, accelerometers and gyroscopes. It has been widely used in the past, namely in marine navigation, but its use is broad and has been applied to aeronautical, automotive and, more recently, robotic and pedestrian navigation (Nebot, 1999) (Fang, et al., 2005). The dead-reckoning concept is often the base of more complex algorithms, such as the Kalman filter used in fingerprinting.

Given that nowadays smartphone devices can have a number of built-in sensors, these methods are well suited for enabling localization for the mobile device. As the principal advantage, they are completely independent of any infrastructure and, once calibrated, they can provide very accurate positing information in virtually real-time. The disadvantage of the method stems from its principle, which accumulates values with error over time. Especially for those cases where only acceleration measurements are available, since double-integration is performed to obtain the position, enormous deviations from the real position very soon appear if speed and position are not "fixed". In many applications GPS is employed to correct these errors, being successfully used as a source of so-called *position fixes*; however, this possibility is subject to the availability of the GPS signal, which can't be assumed for many scenarios, including indoors and underground. For those cases additional fix sources are required, which can be accomplished with the aid of pedometers (Randell, et al., 2003), magnetometers (Goyal, et al., 2001) and existing network infrastructures, e.g. Wireless Sensor Networks (WSN's) (Gadeke, et al., 2011). Dead-Reckoning is referenced due to its importance to localization in general; however it lies outside the scope of the current research.

2.5 LOCATION FINGERPRINTING TECHNIQUES

Location fingerprinting is an empirical method of estimating the location of a *Mobile Station* which requires neither an exclusive infrastructure nor cooperation between the parties. Location fingerprinting methods have been widely used indoors with RSSI measurements due to their complex variability patterns which, for the most cases, are almost impossible to predict. Due to their flexibility, fingerprinting methods can also be employed to AoA and ToA but their applications is rather limited to specific situations. Furthermore, these methods have recently received much attention regarding pattern analysis with imaging and sound signals. Despite interesting, these applications lie outside the scope of this thesis.

Location fingerprinting methods involve an *offline* (or *calibration*) phase and an *online* (or *location estimation*) phase. The *offline phase* consists in measuring the network signal characteristics, also known as fingerprints, at certain calibration points in order to create a map of the network. This map, called *radio-map*, can then be used during the *online phase* to infer the position of the device, in a procedure involving comparing the newly collected signal characteristics against those stored in the map. This characteristic makes fingerprinting to work best for locations where the space complexity imposes deep changes in the signal that makes each calibration point unique (Bensky, 2007).

Several fingerprinting methods exist and they can fall into one out of two categories (Honkavirta, 2008):

- **Static location estimation algorithms:** the fingerprints are individually used in the calculus of a location. They can be further divided into *Deterministic* or *Probabilistic* algorithms.
- **Filtering algorithms.** In this approach, the *radio-map* captures the relations among the calibration points, making it more robust against measurement-wide variations.

Calibration phase

The *radio-map* is created during the calibration phase and is used for every location estimation process. It stores the RSSI values of the signal as a function of their location within an area of interest. *Signal-to-Noise Ratio* (SNR) data is also available but is usually disregarded since the RSSI has a stronger correlation to the location (Bahl & Padmanabhan, 2000). In addition, some factors that can strongly influence the readings are also registered. For instance, the orientation

of the measurement since, due to human body shielding, can reduce the RSSI by 5 dB (Bahl & Padmanabhan, 2000).

Given that different devices may report slightly different RSSI values, the calibration process is performed utilizing the same device for the concerning area, which is also preferably the one used during the online phase. In such circumstances, the RSSI becomes a relative indicator, whose unit and eventual calibration factors introduced by the device are not relevant. Nevertheless the RSSI values are normally given in power units, either mW or dBm.

During the calibration process, from tens up to thousands of samples are taken to characterize each location. In order to reduce the computational demand it is useful, and sometimes required, to preprocess the calibration map to reduce the amount of information to be stored. The stored approximations will depend on the estimation methods used, the most common being their statistical properties: *Mean*, *Variance*, *Median*, or a full *Histogram*. The simplest approach is to store only the mean value, as used in the RADAR system (Bahl & Padmanabhan, 2000). Despite being convenient, this approach completely discards the signal variability, which might help characterizing the location profile. To mitigate that (Kaemarungsi & Krishnamurthy, 2004) suggest to store the variance in addition to the mean, and assume the samples to follow a Gaussian distribution.

In some scenarios, the RSSI distribution can be considered itself as a good characteristic of the calibration points. In order to capture this information, (Roos, et al., 2002) propose storing a histogram of the RSSI. Histograms are then the base of some probabilistic methods, as discussed below.

2.5.1 DETERMINISTIC LOCATION ESTIMATION

In a deterministic approach, estimation is based on the similarity of a measurement and the collected fingerprints. Normally, each measured fingerprint is evaluated independently and the similarity to a given point of the *radio-map* is assessed by the norm of a distance vector, calculated for N channels according to a norm p, as:

$$\|x\|_p = \left(\sum_{i=1}^N |x_i|^p \right)^{1/p}, \quad x = (\bar{y} - \bar{a}_j) \quad (\text{eq. 2.16})$$

In (eq. 2.16) y is the vector of measured RSSI's, and a_j the vector of RSSI of an arbitrary point j of the *radio-map*. For the case of Wireless LAN, each access point (AP) typically provides a channel which, if measureable, represents an additional dimension to the distance vector. The most common norms, p as in (eq. 2.16), are 1-norm (sum, also known as Manhattan distance), 2-norm (Euclidean distance) and ∞ -norm (maximum). The Euclidean distance is the most used one for location fingerprinting (Honkavirta, 2008).

Another norm which is often used in fingerprinting is the Mahalanobis norm. It is defined as the distance of a sample to a distribution defined by the means and deviations of a sample vector (Mahalanobis & Chandra, 1936), formulated as:

$$D_M(x) = \sqrt{(x - \mu)^T \sigma^{-1} \cdot (x - \mu)} \quad (\text{eq. 2.17})$$

Where σ is the covariance matrix and μ the vector with the mean values for each channel. Reformulating (eq. 2.17) considering individual RSSI samples, we obtain:

$$\|x\|_M = \sqrt{x^T \sigma^{-1} x} \quad (\text{eq. 2.18})$$

For better understanding, (eq. 2.18) means that the Mahalanobis norm between two points is the distance x among the points, in vectorial form, squared and weighted by the covariance matrix. In case the covariance is the identity matrix, then it is equivalent to the Euclidean norm.

Nearest Neighbor (NN) and K-Nearest Neighbor (KNN) methods

The Nearest Neighbor (NN) (Duda, et al., 2000) is one of the simplest methods for pattern matching, hence used for location finding as well. It works by selecting from the *radio-map* the point whose norm to the online measurement is smallest, i.e., the point having the closest RSSI value, considered all the channels. Due to its simplicity, however, the method disregards information of the other points with similar characteristics. Even though this might be desirable and working best in some situation (Li, et al., 2006), the method could potentially fall in a local optimum, yielding a solution which is far from the actual position.

To avoid this limitation, the K-NN method (or simply KNN) takes into account the K most similar fingerprints from the *radio-map*. The location estimate (\hat{x}, \hat{y}) is then calculated by an

averaging process which, in its basic form, is given by the arithmetic mean of their coordinates (x_i, y_i) (Lin & Lin, 2005), as:

$$(\hat{x}, \hat{y}) = \frac{1}{K} \sum_{i=1}^K (x_i, y_i) \quad (\text{eq. 2.19})$$

Several modifications to the KNN approach exist in the literature, one of the most relevant being the Weighted KNN. In this approach the K selected fingerprints are given different weights according to the method. For instance, (Li, et al., 2006) propose to use weights as the inverse of the RSSI distance norm, as:

$$(\hat{x}, \hat{y}) = \frac{1}{\sum_{i=1}^K w_i} \sum_{i=1}^K w_i (x_i, y_i) \quad (\text{eq. 2.20})$$

$$\text{where} \quad w_i = \frac{1}{\|x_i\|} \quad (\text{eq. 2.21})$$

In (eq. 2.21) $\|x_i\|$ is the distance, as defined in (eq. 2.16). The authors report that the method performs better than the simple NN ($K=1$), yielding the best results for $K=3$ or $K=4$. For higher values of K it is generally accepted that the method starts performing worse, as points further away are considered and corrupt the averaging (Honkavirta, 2008).

2.5.2 PROBABILISTIC LOCATION ESTIMATION

One of the main drawbacks of the KNN methods is that they don't take into consideration extended information at each sample point, other than a single value, typically mean or median. Such simplification typically disregards the variance, a key indicator of the quality of the sampling and a characteristic of the position (Prasithsangaree, et al., 2002).

The objective of probabilistic methods is to determine the likelihood that the new measurement belongs to a group of signal samples of the fingerprint, characterized by their probability density function (pdf). Such testing is performed based on the Bayes' theorem, and therefore probabilistic methods are also known to follow the Bayesian framework.

$$P(x|y) = \frac{P(y|x) P(x)}{P(y)} \quad (\text{eq. 2.22})$$

Regarding fingerprinting, the Bayes' rule yields the probability of a point in the *radio-map* (x) being related to an online measurement (y) given the likelihood of the measurement to belong to the point distribution $P(y|x)$ (Roos, et al., 2002). Bayes theorem includes the *a-priori* term $P(x)$ accounting for information which benefits some locations over others, which makes sense, for instance, for sequential measurements and tracking. $P(y)$ is used as a normalization constant.

According to the maximum likelihood method, the likelihood parameter is calculated as:

$$P(y|x) = \mathcal{L}(x; y) = \prod_{j=1}^{N_y} f_{V_{xj}}(y) \quad (\text{eq. 2.23})$$

$f_{V_{xj}}$ is the approximated representation of the pdf, for a single point and channel. The likelihood \mathcal{L} of the measurements y belonging to the distribution at point x is calculated as product of $f_{V_{xj}}$ evaluated for all the N_y observed channels.

For the approximation of the pdf function, various ways exist which lie in one of three categories: *Histogram*, *Kernel* and *Parametric* approximations.

The Histogram method

The histogram method is closely related to the need of creating a discrete representation of the fingerprints, and has been independently suggested by several authors (Roos, et al., 2002), (Castro, et al., 2001) and (Youssef, et al., 2002). In the Histogram method, several RSSI histograms for each calibration point are created, one for each available signal source. The histogram is usually created according to the maximum-likelihood method, where the normalized bin frequencies are used as the bin probabilities. Consequently, the method performance also depends on the bin width. Being a discrete representation of the pdf, it can be defined as:

$$f_{V_{xj}}(y) = H_{x,j}(y) \quad (\text{eq. 2.24})$$

The Histogram method can nevertheless suffer from what's known as *incomplete calibration phase*, which shows up as null bins in some parts of the histograms. A common solution, accepted within the Bayesian model, is to add a small fraction of the total probability mass uniformly to all bins (Roos, et al., 2002). These issues are also solved in the *Kernel* and *Parametric* approaches.

The Kernel method

The *kernel density* method or *Parzan window* is another non-parametric method for approximating the underlying probability density function (pdf) of the samples. The method is, by definition, more precise since it doesn't have to "round" a sample to fit a specific bin, but the original sample value is taken into account, and, therefore it is widely used for data interpolation. The approximation is a continuous distribution and, therefore, it allows the result to be calculated analytically, while avoiding the problem with empty bins.

The approximation to the pdf is defined by the averaging of so-called kernel functions. Each Kernel is the continuous representation of a sample, approximated to a parametric distribution, whose center is the average of the sample (Roos, et al., 2002).

$$f_{V_{x,j}}(y) = \frac{1}{N} \sum_{i=1}^N \frac{1}{V_N} K_{x,j} \left(\frac{y - y_i}{h_n} \right) \quad (\text{eq. 2.25})$$

In (eq. 2.25) N is the number of sample groups, between 1 and the sample count, V_n is the sample volume, h_n the group normalized width or window size, and $K_{x,j}$ is the kernel function chosen for the point and channel.

A number of parametric distributions can be used as kernel functions, the most common being Normal/Gaussian, Log-normal and Exponential (Honkavirta, et al., 2009).

To help understanding the approximation performed by Kernel method and the influence of the parameters window size (h_n) and sample groups (N), consider the distribution represented by Figure 12, a bi-modal distribution. The representation is obviously perfectly with infinite samples; however, using a small number of samples, the results depend very much on the parameters. For instance, when only a single sample is used, the approximation to the first mode is good ($h_n=5$), but the second mode is completely lost. This fact raises the awareness that, the more appropriate the kernel function used, the lower the number of samples required to reasonably represent the actual pdf.

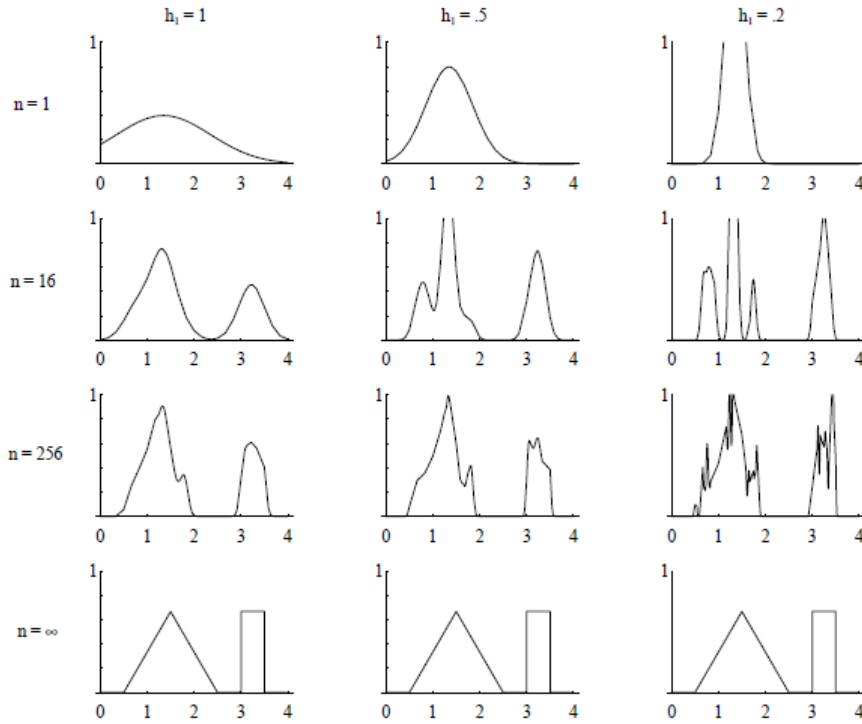


Figure 12 - Pdf approximation by kernel method with Gaussian functions.
Plots for different window' and sample sizes

Parametric methods

In a parametric approach the RSSI histograms are approximated to some known distribution. By using the pdf of a known distribution, the computing of the likelihood becomes simple. Nevertheless, since the RSSI is so highly affected by the space, obtaining good results with this method is a challenging task. The two most common approximations are Gaussian and Log-normal distributions.

The use of the Gaussian distribution to approximate RSSI pdf's has been applied in several works (Haeberlen, et al., 2004; Li, et al., 2006; Kaemarungsi, 2006). However, despite its success, the Gaussian distribution is symmetric and might not capture the RSSI distribution of weaker signals, which frequently exhibit a long tailed shape. In those situations the log-normal distribution might be more suitable (Honkavirta, et al., 2009).

2.5.3 THE FILTERING APPROACH

A different approach to fingerprinting is to consider all the previous measurements in addition to the current one, when calculating the location estimate. Filtering techniques try to capture eventual patterns in the signal variations and use it to better match measured points in the online phase. The use of the earlier measurements is based on the *state model*, where the state of the previous measurement is matched with the current one, accounting for some state and measurement noise generally with zero mean. Although the time-series analysis might require significantly higher computation power, the methods provide better position accuracy than static location estimation (Honkavirta, 2008). Two important filters exist in the literature: the *Bayesian* filter and the *Kalman* filter.

Bayesian filter

The Bayesian filter is the natural extension of the probabilistic approach. It builds exactly on the same base (eq. 2.22), but in this case the *a-priori* term $P(x)$ has now a full meaning: the probable previous positions to help deciding the next position (Honkavirta, et al., 2009). Defining the time index k , the Bayes' expression becomes

$$P(x_k|y_{1:k}) = \frac{P(y_k|x_k) P(x_k|y_{1:k-1})}{P(y_k|y_{1:k-1})} \quad (\text{eq. 2.26})$$

As seen in (eq. 2.26), the probability for a given position at time k (x_k) is calculated given all the performed measurements until the current ones ($y_{1:k}$). After an initialization state, as required by any state model, two phases follow cyclically: the *prediction* and the *update*. The prediction refers to the calculation of the a-priory term, while the update phase is the actual resolution of the Bayes' rule, which accounts equally for the likelihood $P(y_k|x_k)$ but also to the conditional probability of being in that position given the previous measurements (the a-priory term). The calculation of the *a-priori* is usually done using the Chapman-Kolmogorov equation (Gardiner, 1985) which introduces a *transition density* term, accounting for the probability of a next state (or position) to be chosen given the previous one. This term can be modeled as a matrix of probabilities of transitions between cells and, interestingly, this matrix can be defined based on the adjacent cells' information from the building floor's plan (Honkavirta, et al., 2009).

Kalman filter

If *Kalman* filter (Grewal & Andrews, 2001; Kalman, 1960; Kailath, et al., 2000) is one of most well-known filters which, in recursive manner, estimates past, present and future states of an unknown noisy process. Due to its flexibility and relatively low computational requirements, it has been successfully applied to a number of research areas, with special emphasis on tracking of moving devices.

The Kalman filter (KF), in is fact an implementation of the Bayesian filter and, accordingly, it works in two phases: *prediction* and *update*. However, the filter assumes that the models used in the prediction and update phases are linear, and the noise follows Gaussian distribution, i.e., white noise.

Several extensions to the KF have been proposed, some of them tackling the linearity restriction. The most used solutions are the Extended Kalman Filter (EKF), described in detail by (Grewal & Andrews, 2001), and the Unscented Kalman Filter (UKF) proposed by (Julier & Uhlmann, 1997). In both cases, the approach is to approximate the non-linear term by Taylor series expansion; but while the EKF approximates the models with the first derivative, the UKF does the approximation using the second derivative.

A comparison on the performance of the Kalman filter and its EKF and UKF variants regarding mobile navigation is provided by (Ali-Loytty, et al., 2005). For more detail on the filters regarding localization the reader can also refer to (Honkavirta, 2008) and (Figueiras & Frattasi, 2010).

2.6 SUMMARY

Chapter 2 introduced the fundamentals of localization in general. It started by discussing the opportunities and challenges of the wireless medium, which had been mostly exploited for data transmission but the same principles apply and have been researched for localization as well. In this part the most important factors impacting performance are also discussed: Path loss, Shadowing and Fast fading. This part is followed by two classifications of positioning systems, one based on their topology and another based on the functional requirements.

In part 2.3 the several wireless distance measurement principles are introduced. They can be generally categorized according to some transmission property, either propagation time, propagation angle, power loss or even the reach to nearby receivers. These measurements are the pillar for position finding techniques discussed in part 2.4. Among them, fingerprinting techniques have become very popular, as they work for a number of signals and network types, including sound or image matching, and especially with the Received Signal Strength to perform localization. Due the rich diversity of these methods, part 2.5 is entirely dedicated to them, covering deterministic methods, probabilistic or Bayesian approaches and some filters that are also used for localization purposes.

INDOORS AND UNDERGROUND POSITIONING

Despite the good performance and acceptance of global satellite-based (GNSS) and many outdoor location technologies in general, the ability for these systems to perform similarly well – if at all possible – indoors, remains a constant challenge.

Even though the same principles apply for both indoors and outdoors, their performance will greatly vary, a fact closely tied to the substantial differences the environments exhibit and the distinct applications they should serve.

This chapter discusses applications of indoor positioning, followed by a summary of technologies and techniques that allow communication and localization indoors, with emphasis on underground environments.

3.1 APPLICATIONS OF INDOOR POSITIONING

In indoor situations GNSS and other outdoor location technologies are not a viable solution. Furthermore many applications require an accurate, fast, and flexible positioning, tracking and navigation functions.

On the other hand, the possibility of locating indoors allows for a set of applications that wouldn't be possible otherwise, which promise to substantially change our lives for more comfort, safety and eventually entertainment, including the following:

Location-based Services (LBS) – services that provide information relative to the current geographical positions. Examples are hand-held devices that show contents as the user moves, like a navigation system outdoors, or a museum guide in indoors.

- **Assistance in Private Homes** – These include applications ranging from the tracking of objects' position to the motion of people. Examples are controlling TVs with gestures, finding lost keys or even Ambient Assisted Living (AAS), where elderly people are monitored in the event of accident or health crisis.
- **Assistance in Health Institutions** – The fast location of personnel in hospital and health centers has become of major importance, mostly in urgencies, and for patients in case of sudden severe problems. Moreover, precise positioning is required for robots assisting during surgeries.
- **Environment Monitoring** – Some activities require the monitoring of physical properties of materials and infrastructures, like temperature, pressure, deformation. These properties can be measured by grids of sensors forming so-called Wireless Sensor Networks that can calculate positions using cooperative algorithms.
- **Safety and Rescue** – Indoor position capabilities can be of extreme importance for coordination of safety and rescue operations by the police or fire brigades. Besides the location of the emergency team elements, the tracking of workers in hazardous areas might show to be extremely useful in speeding up assistance in case of an accident.
- **Transportation** – Automated driving and guided parking might be doing their first steps thanks to properly equipped cars and parking garages.
- **Industry** – Many mechanical processes of assemblage and displacement will benefit from better positioning in order to become more automated. One of the most notable examples are assembly lines of car manufacturing industry.
- **Logistics and optimization** – tracking the position of goods and personnel enables the fast retrieval/routing of goods and allocation of people to the respective process. If required the process might be optimized by relative closeness. Such optimization is key in logistics centers, but can also improve efficiency in administrative businesses, where documents have to be tracked and processed.
- **Underground activities** – Tunnels, mines and other underground facilities are often environments of extreme conditions (dust, darkness, humidity, instability and/or irregularity of walls) and therefore hazardous for workers. Localization plays a central role for safety although it might also improve the industrial process in cause, like the installation of equipment.

3.2 CHARACTERIZATION OF INDOOR POSITIONING SYSTEMS ACCORDING TO SIGNAL TYPE

There are numerous systems for indoor localization. They are usually classified according to their underlying technology, as it directly impacts their general characteristics and performance figures. Table 1 presents an overview of the classes of technologies used for indoor localization and their typical parameters.

It can be seen that, in general, the accuracy and coverage a certain technology is able to provide will highly define its domains of application. For instance, it becomes obvious the use of tactile and polar systems in the automotive and metrology domains, since accuracies better than one millimeter are required. These relations can also be graphically represented, as in plots of Figure 13 and Figure 14 (Mautz, 2012). When superimposing both plots one can imagine a direct matching between technologies and their applications.

TABLE 1 - OVERVIEW OF INDOOR POSITION TECHNOLOGIES: TYPICAL PERFORMANCE AND APPLICATIONS

Technology	Accuracy	Coverage [m]	Measuring principle	Application
Infrared	cm – m	1 - 5	thermal imaging, active beacons	people detection, tracking
Sound	cm	2 - 10	ToA	hospitals, tracking
WLAN/WiFi	m	20 - 50	RSSI fingerprinting	pedestrian navigation, LBS
RFID	0.1 - 1 m	1 - 50	Proximity, fingerprinting	pedestrian navigation
Ultra-Wideband	cm - m	1 - 50	ToA	robotics, automation
Self-Infrastructure	cm - m	Infrastructure	Varies	ambient assisted living
Improved GNSS	~10m	“global”	A-GPS	location based services
Magnetic systems	mm - cm	1 - 20	Fingerprinting	hospitals, mines
Cameras	0.1 - 100 mm	1 - 10	Angle from images	metrology, robot navigation
Inertial Navigation	1% of path	10 - 100	Dead reckoning	pedestrian navigation
Tactile and Polar systems	µm - mm	3 - 2000	Tactical, interferometry	automotive, metrology

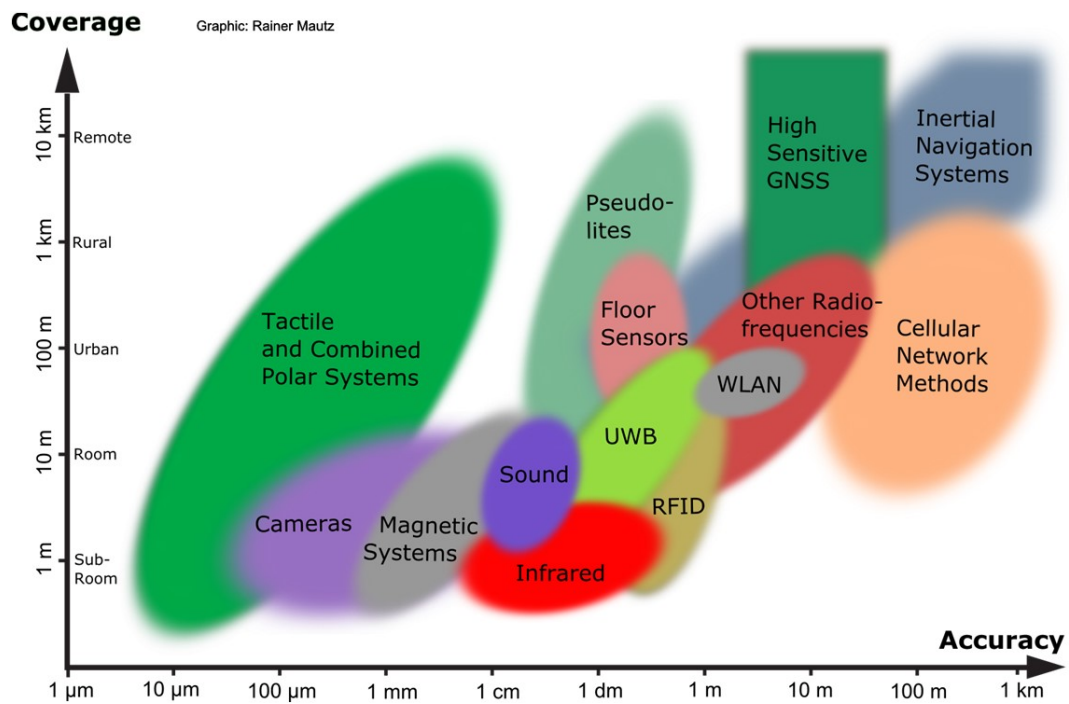


Figure 13 - Technologies according to coverage and accuracy levels

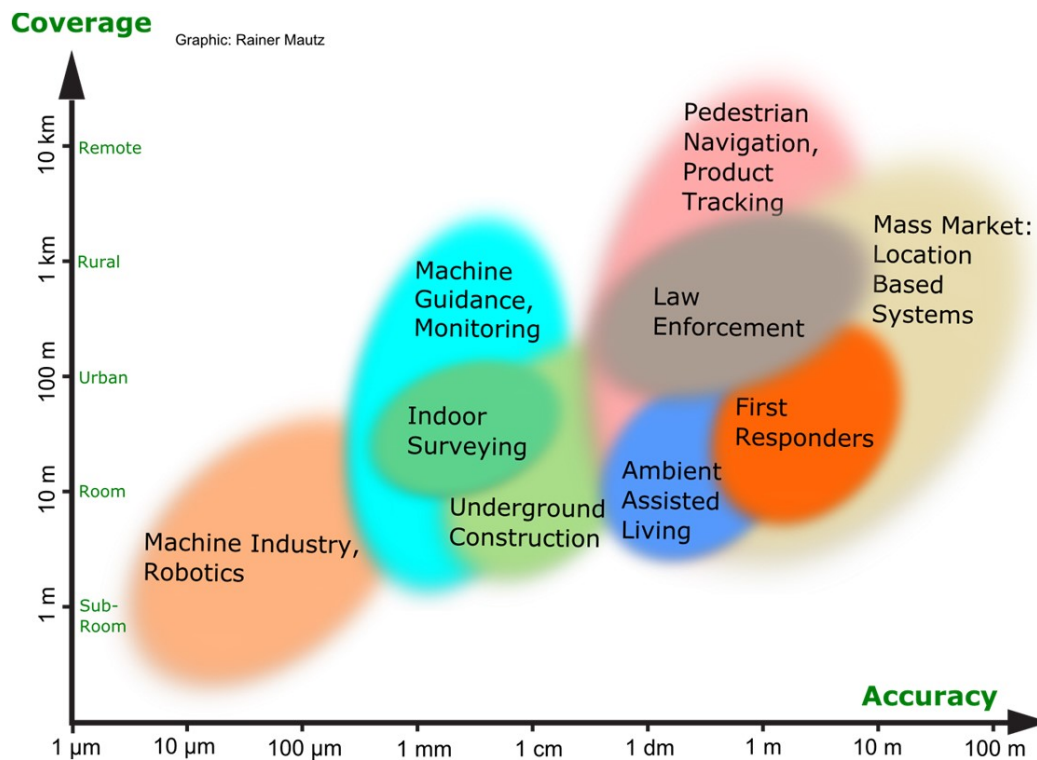


Figure 14 - Localization applications according to required coverage and accuracy

In the case of underground constructions, in order to meet the suggested accuracy levels (0.1 to 10 cm) and coverage requirements (10 to 100 m), magnetic, sound, pseudo-lites and Ultra Wide Band (UWB) technologies are typically used. However, from the given information, there is no single technology which fully meets these requirements, even though only a pair (of requirements) was specified. Furthermore, as stated before, these parameters depend on the specific application, and therefore a comprehensive analysis is required.

3.3 CHALLENGES INDOORS AND IN UNDERGROUND MEDIUM

Indoor localization can be particularly challenging for several reasons, arising from the fact that there are walls and objects around the confined spaces where transmission is to occur (Mautz, 2012).

These conditions favor several signal effects, which are unusually undesirable as they highly impact on the measured signal properties, including propagation delay and the power. In particular, from those presented in Chapter 2 section 2.1, the following effects are particularly significant:

- **Multipath** due to signal reflection
- **Non-Line-of-Sight** (NLoS) due to signal blockage and reflection
- **High Attenuation** due to distances and obstacles
- **Scattering** due to different material densities traversed
- **Dynamic** conditions, due to the movement of people and objects

The large majority of positioning technologies have been designed for indoor environments; however most existing commercial products have been developed for use in office buildings, airports, shopping malls, factory plants, and other similar spaces. Nevertheless these solutions usually don't meet the requirements for underground scenarios, which present distinct properties and challenges.

3.3.1 UNDERGROUND MEDIUM PROPERTIES

Underground tunnels and mines, or even underwater wells and caves, present a very particular scenario when compared to surface and other indoor environments. They are

structurally different and offer different conditions in terms of localization opportunities. Still, tracking and navigation for such spaces play a central role for safety and in rescue operations, as well as for supporting specific activities or for scientific research activities in other fields.

These spaces are particularly difficult scenarios for radio transmission, a fact that has been observed since the 1920's following the boom in mining activity. Such difficulty is associated with their physical characteristics which have a negative effect in the transmission of electromagnetic waves (Delogne, 1991), the most significant being:

- confined spaces encompassed by irregular surfaces
- circular or rectangular tunnel sections
- presence of halls, cross-cuts and blockages
- Limited Line-of-Sight (LOS)
- Presence of ionized air, humid and warm conditions
- Presence of additional gases
- Structural changes

In such conditions, comparing to indoors, the adversities on the transmission of wireless signals are further emphasized:

- **Extreme path-loss:** high losses due to material absorption and humidity.
- **Reflections and Refractions:** Due to proximity of the walls, reflection effects can be quite strong, resulting in a waveguide effect. Furthermore, because of the irregular nature of the walls, reflections can be quite distorted which will turn into noise.
- **Multipath fading:** the random combination of multiple propagation paths leads to fast variations in the signal strength. Hence, this effect is also known as fast-fading.
- **Dynamic conditions:** Besides the movability of people and objects, the tunnel dielectric properties (permittivity and permeability) change with the temperature. As a consequence, besides different propagation paths, also the propagation speed is subject to variations.

- **Noise:** electromagnetic noise in the environment will interfere with communications, in particular noise caused by motors, power lines and appliances since they operate in nearby frequency bands.

3.3.2 REQUIREMENTS FOR UNDERGROUND CONSTRUCTIONS

In the case of underground constructions, there are usually very specific needs in terms of localization. These needs reflect the specificities of the physical place and the application, which are completely different to surface indoors, like Ambient Assisted Living (AAL), and even among themselves, e.g. a motorway tunnel from a coal extraction mine. In a study by (Schneider, 2010) four surveying tasks are common in underground constructions, all having different accuracy and latency requirements: heading guidance, deformation analysis, machine guidance and profile control. Table 2 summarizes the difference between those scenarios, identified as “Underground constructions”, against typical surface AAL. In the third column also the target requirement values for localization in the LHC tunnel are presented for comparison. As can be seen, significant differences arise with respect to a typical underground construction not only because the space is different but, most importantly, because the intended application differs quite considerably. Due to the specifics of the case, existing out-of-the-box solutions cannot be used and the system has to be specifically designed.

TABLE 2 - COMPARISON OF REQUIREMENTS BETWEEN DIFFERENT INDOOR SCENARIOS

Requirement name	Target value for AAL	Target value for Underground Constructions	Target value for CERN LHC
Accuracy	0.5 - 1 m	1 - 5 cm	10 -50 m ~ 1 m (high accuracy area)
Range	Living area	20 - 50 m	27 km
Cost	As low as possible	cost of surveying station (<50.000€)	As low as possible, incremental
Output data	2D relative position	3D coordinates	1D position along tunnel
Interface	Network	GUI, operated by technicians	GUI, operated by technicians
Robustness	High, subject to good conditions	High, against impacts, dust, deformation, vibrations	High, against vibrations, dust, interference
Availability	> 90%	80%, with realtime results	> 95 %
Scalability	None	Case specific	Upgradable to high precision where required.
Number of users	Very few	Case specific	As many as possible. Min.: 10
Intrusiveness	Non-invasive	Case specific	Shall not disturb existing procedures/equipment
Approval	End user	Case specific	Internal regulatory groups

3.4 TECHNOLOGIES FOR UNDERGROUND COMMUNICATIONS

Although tunnels do, to a certain extent, propagate wireless signals, it may be very difficult to predict the signal characteristics after a few hundred meters. Even if regular signal measurements were performed to assess these characteristics, network planning would become a laborious task and, moreover, many situations would still impose serious obstacles to natural propagation, including non-continuous tunnel sections, very irregular surfaces, caverns, water leaks. Because of these problems, new communication techniques have been developed that cope with such inhospitable underground characteristics.

Underground communication techniques can be classified according to the main underground medium used (Bandyopadhyay, et al., 2010): Through-the-Air (TTA), Through-the-Wire (TTW) and Through the Earth (TTE)

3.4.1 THROUGH-THE-AIR (TTA)

TTA communications comprise a whole set of radio techniques which don't require any specific propagation medium, other than air. Natural propagation is a primary means of communication which, besides all limitations, can be adequate for regular shaped tunnels or specific applications. There are mostly two techniques:

1. **Free tunnels as waveguides** - Using the tunnel itself to guide the waves.
2. **Wireless Mesh networks** - In which several access points cooperate to create a resilient and wide coverage network.

Free tunnels as waveguides

In an empty tunnel, propagation behaves similarly to that occurring in hollow waveguides (Chiba, et al., 1978) in which only frequencies above a threshold imposed by the tunnel size and shape will propagate properly. This frequency is known as the cut-off frequency of the medium, for which the standard equations for metallic waveguides still provide good approximations.

According to propagation laws in circular waveguides, the cut-off frequency for the dominant mode TE₁₁ is given by

$$f_{c_{mn}}^T = \frac{\chi_{Tmn}}{2\pi r \sqrt{\mu\epsilon}} \Rightarrow f_{c_{11}}^{TE} = \frac{1.8412 \cdot c}{2\pi r} \quad (\text{eq. 3.1})$$

Thus, the relation of the cut-off wavelength and the waveguide radius can be expressed as:

$$\frac{c}{\lambda_c} = \frac{1.8412 \cdot c}{2\pi r} \Rightarrow \lambda_c \approx 0.3r \quad (\text{eq. 3.2})$$

This relation confirms the rough approximation of both parts having the same order of magnitude, many times used as a reference in tunnels.

Propagation of waves whose frequency is above cut-off is known as *Natural Propagation*:

$$\lambda \leq 0.3r \Rightarrow f \geq \frac{c}{0.3r} \quad (\text{eq. 3.3})$$

Experimental works in (Chiba, et al., 1978) show that the tunnel diameter should be from several to ten times larger than the free-space wavelength for natural propagation to occur. For instance, in a tunnel of 2 m diameter, 500MHz signals are expected to “naturally” propagate well.

Wireless Mesh Networks (WMN)

A new approach to TTA has been explored for tunnel communications based on the development of specialized Wireless Mesh Networks. Cooperative networking techniques have been successfully applied to tunnels and underground facilities, defining a field denominated as Wireless Underground Communication Networks (WUCNs) (Akyildiz, et al., 2009). These networks consist of wireless devices that operate below the ground surface which are either (i) buried completely under dense soil or (ii) placed within a limited open underground space such as mines and road/subway tunnels. Clearly taking advantage of the ever less expensive network elements, this approach focuses on the devices' cooperation to form a network with remarkable resiliency features. According to propagation medium, they fall undoubtedly in the TTA and TTE categories.

3.4.2 THROUGH-THE-WIRE (TTW)

TTW techniques require some wired communication infrastructure. *Twisted pair, Coaxial cable, CAT5/CAT6, trolley cable, optical fiber and leaky-feeder* are some of the most used types of

cable, each of them with its own set of characteristics addressing different problems. *Leaky-feeder* cables are among the most popular for wide coverage in mines.

Wired techniques cope well with tunnel constraints, including irregular shapes, the presence of obstacles and separation walls. Furthermore, these can be (and usually are) of very high quality, which are not susceptible to corrosion and are resistant to small damages and fire to a certain extent. They are therefore quite an adequate option for tunnels with little change in its structure. The drawback of such systems relates to its vulnerability, as a cable cut will terminate communications beyond the defect.

Signal transmission recurring to *Leaky-feeder* has a long history of success in tunnels since the 1980s (Novak, et al., 2010). It consists of a cable which allows signals to leak into or out of the cable along its entire length, behaving as a very long antenna. It allows for two-way mobile communication for a longer range as a result of lower attenuation when compared to *Free Space propagation* in a mine.

There are a few possibilities for cables in leaky-feeder systems (Bandyopadhyay, et al., 2010), as described below:

- **Long-wire antennas** – antennas that are considerably long - usually over 10 m - and therefore they receive multiple bands and radiate quite efficiently. Although their gain is lesser when compared to multi-element antennas, their mechanical and electrical simplicity allow them to be a suitable option for tunnels.
- **Twin-wire feeders** – They consist of two parallel conductors, whose current flows in opposite direction. Therefore, with appropriate spacing between the wires, the fields can cancel among themselves avoiding signal emission or pick up.
- **INIEX/Delogne system** – To avoid the extensive use of repeaters, discrete radiators or *mode converters* are installed at calculated intervals in a standard non-leaky cable, which introduce a complete annular gap in the outer conductor.
- **Slotted Shield leaky-feeder cable** – Slotted shielded cables (Figure 15), also known as Leaky Coaxial cables (LCX), are designed so that the outer shield of the coaxial cable has apertures about every 2 cm, but it depends on the application. Although they are usually more expensive than the other options, the frequency selectivity feature of these cables allow them for superior performance. They have been quite successful in numerous applications and rapidly this type became the reference within *leaky feeder* systems.

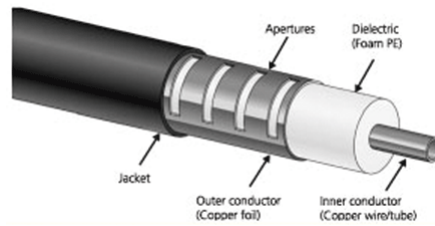


Figure 15 - Slotted shield leaky feeder cable

- **Loose-Braided cable** – Contrary to a fully shielded coaxial cable, if the cable coverage is loosely braided (typically 63% or 67% of the cable surface), power is likely to leak through it. However, loosely braided cables have higher losses than slotted shielded cables and usually provide lower coverage.

3.4.3 THROUGH-THE-EARTH (TTE)

Electromagnetic waves can propagate through soil. They face, nevertheless, a more hostile medium which introduce higher attenuation factors when compared to air, as well as other effects, like reflection and refraction of the signal. These medium characteristics are mostly due to the very low yet variable conductivity of most soil elements (Yenchek, n.d.) - see Table 3.

In TTE communication systems, low frequency electromagnetic waves have been used to mitigate the high attenuation effects, to the point that they penetrate several hundreds of meters. The drawback is that, at such frequencies, the available bandwidth is rather short which limits communication to very low data rates, in the order of a few kbit/s.

TABLE 3 - CONDUCTIVITY OF COMMON SOIL ELEMENTS

Material	Conductivity (σ [S/m])
Dry limestone	0.001
Sandstone	0.01
Salt	0.15
Coal	0.25
Salt water	5

3.5 A SURVEY ON STATE-OF-THE-ART RELATED LOCALIZATION SYSTEMS

Many of the techniques that have been proposed for positioning inside office buildings and similar spaces are also being explored for positioning in underground tunnels. Most of them rely on the use of one or more sensors to measure some characteristics of the surrounding environment or how signals propagate in space. These signals are then processed using range-based, time of flight, angle of arrival or scene analysis approaches, together with geometric algorithms, to produce an estimate for the position of a given device. A quite comprehensive survey of indoor positioning technologies is done by Mautz (2012). Most of the existing positioning systems for indoor use are 2D, meaning that the position of the device or person is estimated in a two-dimensional Cartesian coordinate system. These systems are often evaluated based on their accuracy, defined as the average positioning error or as the maximum expected error for a given percentage of the estimates. The error is, in this case, the Euclidean distance between the estimated and the real positions. For multi-floor buildings, the position estimates are usually described by a pair of coordinates (x,y) plus a floor identifier, leading to what are known as 2.5D systems. Some systems are able to provide real 3D position estimates, and these are often very accurate. At the other extreme are systems that provide position estimates along a line, such as the distance from the entry point on a tunnel. These are 1D positioning systems. Most of the solutions for tunnels are 1D, but 3D systems also exist for underground positioning. Some examples of these systems are described next.

3.5.1 UNDERGROUND AND MINE SYSTEMS

Magnetic

The InfraSurvey is a 3D positioning system based on the magnetic fields generated by mobile underground transmitters and detected by receivers at the surface (InfraSurvey, 2013). Orientation of the transmitters can also be estimated. According to InfraSurvey, the position and orientation of the transmitters can be estimated at up to 300 meters below the surface with an accuracy of 1 meter, by taking advantage of the low absorption of magnetic fields by rocks.

Ultrasound

Mines are one of the underground contexts for which many positioning systems have been proposed. Aiming to develop a positioning system for extreme conditions, Misra proposed a solution based on a wireless sensor network and ultrasound ranging in order to provide positioning services without the need of a fixed infrastructure (Misra, et al., 2011).

WLAN

Another solution for positioning inside coal extraction longwall mines has been proposed by Andreas Fink, aiming to automate the placement of machinery (Fink, et al., 2010). This solution combines RSSI-based positioning and inertial navigation to increase the positioning accuracy to better than 1 meter.

Safety in narrow-vein mines can also be improved by deploying positioning systems for localizing and tracking workers and equipment. For these scenarios (Dayekh, et al.) proposed a system based on cooperative spatio-temporal diversity where fingerprints are collected from multiple access points at different time instants and combined using Artificial Neural Networks (ANN) to estimate the 1D position of moving objects (Dayekh, et al., 2011). This cooperative approach is claimed to outperform previous solutions, also based on ANN, that use spatial or temporal diversity only. The reported results point to an accuracy of better than 25cm for 90% of the estimates.

Pseudolites

Some solutions have also been proposed for car and train tunnels. The use of pseudolites has been proposed for tunnels where GPS signals are unavailable, to provide positioning at centimeter-level accuracies (Michalson & Progre, 2000). In this work, the tunnel geometry is taken into consideration to eliminate the undesired effects of multipath propagation. By selecting appropriate places for positioning the antennas in straight tunnels, centimeter-level accuracies can be achieved. Other tunnel geometries, such as curved tunnels, require further study.

RFID

The use of RFID (Radio Frequency Identification) technology combined with GPS and gyroscopes has also been exploited to improve the positioning and navigation of vehicles in road tunnels and downtown areas (Chon, et al., 2004). The basic idea relies on embedding RFID tags

into the pavement of roads and on the installation of RFID readers in the vehicles. The information obtained by the readers when a tag is detected on a vehicle is then combined with GPS and gyroscope data to produce very accurate positioning estimates.

3.5.2 LOCALIZATION SYSTEMS EXPLOITING LEAKY-FEEDER CABLE

Due to the geometry of tunnels, Slotted-shielded *leaky-feeders*, are particularly adequate to provide uniform radio communication services. Recently, these cables have also been considered for supporting positioning systems

Dedicated infrastructure

Nakamura proposed a positioning system based on a leaky-feeder cable for tracking rescue workers in tunnels and passages in underground facilities. The basic idea is to inject a non-modulated pulse at a carrier frequency of 2.4 GHz into the cable, let the tracked devices receive these pulses, and down-convert them to 1.2 GHz pulses that are transmitted back to the cable (Nakamura, et al., 2010). The position along the cable is estimated from the time difference between the transmitted and received pulses. An accuracy of about 1 meter over a section 100 meters long has been reported, but larger errors, up to 10 meters, have been observed in some sections of the cable.

WLAN

The use of leaky coaxial cables for indoor positioning has also been reported by other researchers (Weber, et al., 2010; Engelbrecht, et al., 2010; Engelbrecht, et al., 2011; Weber, et al., 2009). Weber (2010) evaluated the performance of WLAN fingerprinting over leaky coaxial cables using several alternative positioning algorithms. The reported results show that an accuracy of around 8 meters (at 80% probability) can be obtained with standard leaky coaxial cables either by post-processing the fingerprinting database, or by using KNN algorithms or Kalman filters. When using a new type of cable particularly adapted for positioning, featuring higher longitudinal attenuation (Weber, et al., 2011), they were able to increase accuracy to 4m. Engelbrecht (2012) also proposes new leaky coaxial cables to support positioning inside public transportation trams. Experimental results obtained along a 9 meters long wagon of a tram, with a leaky coaxial cable deployed on the wagon ceiling, prove the feasibility of this approach for positioning, with accuracies around 1.3 meters (95,45% confidence).

3.5.3 LOCALIZATION WITH GSM FINGERPRINTING

Indoors localization systems based on fingerprinting have been widely explored, mostly over WLAN, achieving very interesting results even without incurring investment on infrastructure. Nevertheless, fingerprinting has also been explored with GSM signals, which is relevant for the current studies. This fact is highly motivated by three important factors: (1) GSM networks are widely deployed and provide a very dense coverage over extended areas, (2) the maturity of the technology allows for easy leverage of existing hardware for new applications, (3) it operates in a licensed band and therefore interference from third party devices is unlikely to occur. The latter is indeed critical for the case of the LHC.

Many studies and experiments have been made in this direction. Accuracies of up to 5 and 75 meters for indoor and outdoor environments, respectively, have been found by (Varshavsky, et al., 2006). In an experiment by Veljo Otsason (Otsason, et al., 2005) on a three-story building, by accessing information of the 6 strongest cells and up to 29 visible others, effective identification of floors was achieved, while 2D accuracy varied between 7 and 19 meters at 90% confidence. Due to the relatively low accuracy levels, many approaches have been explored in order to improve it in GSM networks. For instance in (Denby, et al., 2009) the use of all 488 GSM carriers in RSSI fingerprints is analyzed in order to distinguish between rooms (0.5-D). The approach achieves successful classification rates up to 97%, against 90% when using up to 35 carriers. Alternatively, some researchers tried improving the results by considering other signal sources. For instance (Zhou, et al., 2008) proposes the use of fingerprinting methods with signals from both GSM and IEEE 802.11b networks and reports accuracy improvement in the order of 95%, where GSM alone could achieve 5 meters at 90%.

Unfortunately, studies of GSM fingerprinting for localization over other network infrastructures, other than cellular broadcasting, are apparently non-existent or undisclosed.

3.5.4 HIGH ACCURACY LOCALIZATION WITH DEDICATED INFRASTRUCTURE

The possibility of adding positioning capabilities to existing network technologies has been seen as a success factor, mostly due to their reduced cost when compared with dedicated infrastructures. Two examples are the basic localization method used by mobile operators to locate their subscribers and WLAN fingerprinting which had become so popular. However, the majority of these systems suffer either from limited accuracy figures or from limited coverage.



Figure 16 - Photos of dedicated infrastructure high resolution positioning systems
(a) Active badge, (b) Cricket, (c) Bat

Alternatively, dedicated infrastructure methods for accurate indoors positioning tend to work more resiliently.

Infrared systems

The Active Badge system (Hopper, et al., 1993) is a reference system whose main objective is to locate people in university or work campus. Each user wears an active badge which periodically emits infrared signals and a grid of sensors captures them to calculate the position within 5-10 m accuracy.

Ultrasonic

Higher accuracy system systems use frequencies in the ultrasonic spectrum - the Cricket (Priyantha, et al., 2000) and the Bat (Ward, et al., 1997) - and obtain accuracies ranging from a few meters to few centimeters.

Ultra-Wideband (UWB)

Also ultra-wideband technology has become quite successful in achieving centimeter level accuracy in indoor environments (Gezici, et al., 2005). Although they can provide quite interesting accuracy figures, all these solutions require the installation of their own and dedicated infrastructure. Therefore their application is usually restricted to situations where localization is absolutely critical and their area of operation very limited.

3.5.5 COMPARISON

A summary of the claimed performance of each analyzed system is given in Table 4. Despite the high accuracy figures, most of them are either limited to a specific range, e.g. InfraSurvey up to 200m, while others are simply limited by the infrastructure and were mostly tested for short sections, below 100m. Other factors, including cost, are very difficult to assess/estimate mostly for systems that are still in an early development state. For those reasons the table was deliberately left with the essential set of characteristics needed for comparison.

As a last note, it is also possible to understand that all systems offering accuracy in the cm-level require some kind of infrastructure. Therefore those allowing for larger range depend on the extension of the infrastructure itself. This fact, due to the very long range to be covered, motivated the development of a method that avoids the installation of extra infrastructure.

TABLE 4 - PERFORMANCE OF THE MENTIONED INDOOR SYSTEMS

System	Group	Accuracy	Range	Output data
InfraSurvey	Magnetic	1-100 m	200 m	3D
Misra 2011	Ultrasound	2 cm	45 m	2D
Fink 2010	WLAN	1 m	Infrastructure	2D
Dayekh 2011	WLAN	25 cm	75m	1D
Michalson 2000	Pseudolites	cm-level	500 m with 6 pseudolites	3D
Chon 2004	RFID	Tag spacing	Infrastructure	2D
Nakamura 2010	WLAN leaky	1-10 m	Up to 300 m	1D
Weber 2011	WLAN leaky	4 m	75 m	1D
Engelbrecht 2012	WLAN leaky	1.3 m	9 m	1D
Otsason 2005	GSM	7-19 m	Building	2D
Denby 2009	GSM	Room level	Building	Room
Zhou 2008	GSM / WLAN	5 m	Building	2D
Active Badge	Infrared	5-10 m	Infrastructure	3D
Cricket	Ultrasonic	cm-m level	Infrastructure	3D
Bat	Ultrasonic	cm-m level	Infrastructure	3D
Gezici	UWB	cm-level	Room	3D

3.6 SUMMARY

This chapter focused on localization specifically for indoors and underground environments. It starts by discussing the applications of indoors positioning, followed by a characterization of the existing indoor localization technologies according to the signal type.

On a next section, an analysis of the requirements specific to underground tunnels is performed, and they are compared to those typical indoors. Additionally, a characterization of the requirements for localization in the LHC tunnel is also provided for the first time, where it is clear that the project has very specific constraints and objectives, and therefore a new system must be designed. Section 3.4 then characterizes the three different approaches for underground signal transmission: Through-the-Air, Wire and Earth (TTA, TTW, and TTE respectively). A very significant approach in TTW is the use of slotted shield leaky coaxial cable, or simply leaky-feeders, as they enable dense and wide coverage of long hauls due to their relatively low attenuation. These cables are present in the current tunnel setup and are exploited for localization purposes.

In the last section of the chapter a number of state-of-the-art studies and technologies are mentioned which are relevant for the current PhD work. Among them there are works on localization for underground mines, systems working over *leaky-feeder*, analyses of fingerprinting with GSM networks and high-accuracy systems with dedicated infrastructure.

As understood by the comparison, there is no single system alone which can enable localization over a wide range without starting to lose accuracy. A good example is the InfraSurvey system, which claims accuracies in the order of 1% of the distance between emitter and receivers. The exception to that rule are systems whose infrastructure is extensible by nature, like RFID, WLAN or other beacon networks. However, deploying a dense network of beacons/tags over an extended area might become cost prohibitive. In order to meet the localization requirements in an area as long as the existing accelerator tunnels, this work investigates the approach of using the existing leaky-feeder network without modifications for localization, with eventual improvements for specific areas. The evaluation of the performance of such approach is presented in the next chapters.

RSSI CHARACTERIZATION OF TUNNEL NETWORKS OVER LEAKY-FEEDER CABLE

The CERN accelerator tunnels and experimental halls present a unique scenario regarding localization, offering interesting opportunities but imposing challenging requirements. This chapter presents an in-depth analysis of the power profile observed for the GSM network deployed over leaky feeder cable in the tunnel, for various conditions and scenarios. Tests with WLAN are performed as well. The results provide valuable insight on the current environment characteristics regarding the propagation and stability of electromagnetic signals, which has a direct impact on the localization solutions.

4.1 RSSI FINGERPRINTING IN THE LHC

Many parameters were analyzed when selecting technologies for localization in the CERN LHC. Besides the technical difficulties the medium presents by itself and the risks of interference, the high levels of radiation present in the LHC invalidate any solution requiring installation of local hardware.

4.1.1 MOTIVATION FOR FINGERPRINTING WITH GSM OVER LEAKY-FEEDER

During operation periods, the LHC machine accelerates particles to very high energy and therefore the tunnel is classified as a high radiation area and made non-accessible. Due to the radiation levels, non-specialized hardware would fail after some days of LHC operation and sensitive devices like radio transceivers are definitely among the most affected classes of electronics. In line with the existing technical solution for tunnel communication, the existence of a network deployed over *leaky-feeder* was found to be an interesting opportunity to overcome

that limitation. It provides wide coverage in the tunnels and is very reliable. Therefore, this medium was taken into consideration for the design of the localization solution.

Among indoor location techniques, those based in the Received Signal Strength Indicator (RSSI) are of particular interest since they require neither the installation of extra infrastructure hardware nor allocation of extra spectrum. Besides the simplicity, RSSI methods do not require additional emitters therefore eliminating the risk of interference.

RSSI fingerprinting shows up as attractive as challenging. Although this is effectively a 1-D localization problem - as only one coordinate axis (along the tunnel) is required – the differences to other indoor scenarios are notable and they might introduce serious issues. On the one hand, localization is to be available along all tunnel's length, i.e. nearly 27 km, which besides possessing quite different shape from office and other spaces, is much beyond the length of any other studied indoors location system or experiment. On the other hand, it is limited to the existing network infrastructure. In the LHC the only network available throughout the tunnel is GSM providing typically two channels per sector.

4.1.2 EXPERIMENTS WORKFLOW

To evaluate the applicability and performance of RSSI fingerprinting methods over the *leaky-feeder* in the LHC tunnel, a series of experiments were conducted. Due to machine

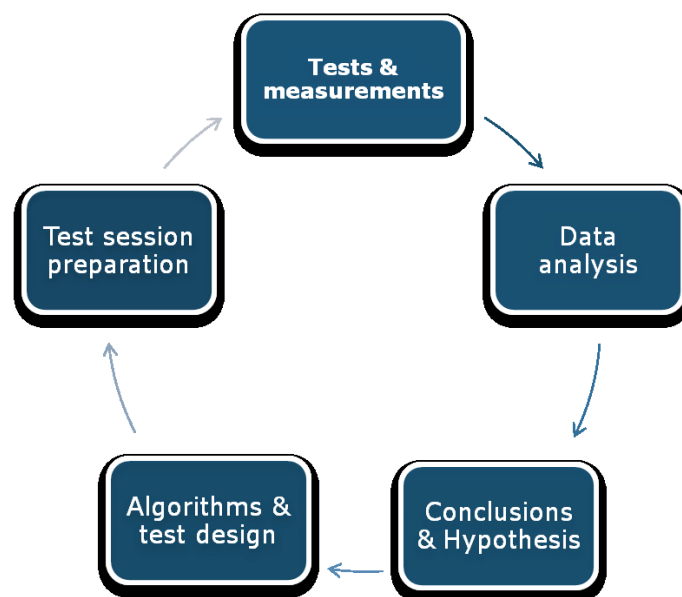


Figure 17 - Tests methodology cycle

operation, data collection was only possible during short-time maintenance periods. Tests and collection tools had to be prepared beforehand and sequent phases of analysis were taking place, to extract conclusions and steer the next tests to be performed. The execution of these activities has therefore been made in a cyclic fashion, where each iteration is delimited by a measurements session in the tunnel, as suggested by Figure 17. Since some experiments were conducted several times at different times, several data sets were collected. These explain the presence of several sessions in the data presented in the next sections.

The first series of the experiments characterize the RSSI profile in the tunnel in several different scenarios, for GSM and then WLAN networks. In a second series, presented in Chapter 5, this evaluation is performed in real-world conditions, where some localization algorithms are tested and benchmarked against a *radio-map* built from the collected RSSI data.

4.2 CHARACTERIZATION OF THE GSM RSSI PROFILE

The experiments were conducted in a sector of the LHC comprising both straight and bending sections. With the help of mobile phones, thousands of GSM RSSI samples were collected to characterize the network and create the *radio-maps*.

4.2.1 LEAKY-FEEDERS NETWORK

GSM network coverage is available all along the tunnel's length via a set of leaky-feeder cables installed at nearly 2 m from the ground. For each tunnel section, two radio channels with distinct radio signals are injected at each cable's ends, therefore creating two GSM cells. Referring to Figure 18, one can see the micro Base Stations (represented as red squares) and the coupling/amplification points of the signal into the leaky-feeder (as pink arrows). Besides the GSM network, also an emergency VHF network was carried along which is now being replaced by TETRA.

As a consequence of this configuration, as one goes along the tunnel, one of the radio channels gets stronger while the other attenuates (Pereira, et al., 2011). According to the vendor specifications (RFS World, 2010), the cable is specially designed for tunnels, providing low coupling loss variations. It propagates electromagnetic waves of up to 1950 MHz and it exhibits a longitudinal loss of 3.16 dB/100m at 900 MHz.

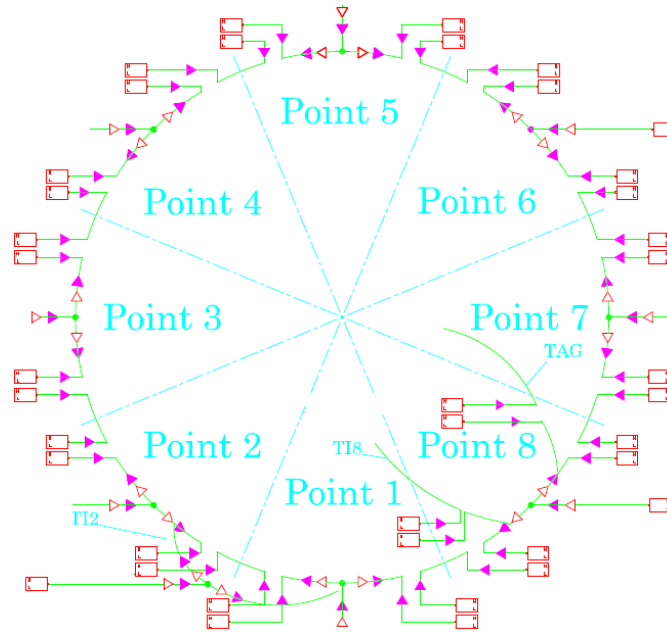


Figure 18 - GSM frequencies along the tunnel.
The pink arrows represent the injection points of GSM frequencies

4.2.2 EXPERIMENTS SETUP

In an initial phase, to characterize the network signal strength profile, several types of measurements were carried out. However, in GSM networks, terminals can only be associated to a single cell and, except for specific vendor solutions, information about the neighbor cells is not directly accessible through the terminals' APIs. Nevertheless, they continuously monitor the conditions of adjacent cells so that the network can perform informed handovers and maintain the channel quality as high as possible. Furthermore several aforementioned studies indeed made use of the neighbor cells' information to increase the performance of fingerprinting methods. In order to continuously monitor and store the signal strength of the network a custom device was setup.

In our tests we used Nokia 6150 mobile phones in which we enabled the NetMonitor menus (see Figure 19). These additional pages of information allowed us to individually acquire the signal strength of the 6 strongest cells, which was updated nearly every second. All fingerprints were automatically recorded to a laptop running a capture and parsing software taking advantage of the Gammu utility (Čihař, online). Three of these terminals were used in parallel, controlled simultaneously by a custom fingerprint collection software. This configuration

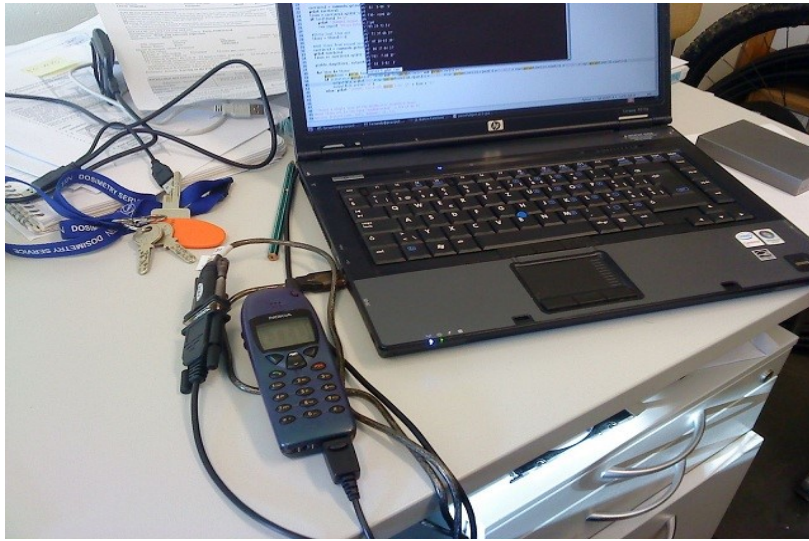


Figure 19 - Equipment used for data collection

enabled the collection of triple the amount of fingerprints in the same time frame and provided valuable hints on the signal changes on a short spatial scale.

Among the performed experiments, the following are of particular interest:

- **Detailed longitudinal measurements**, with fingerprints taken every 40 meters in a section of 600 m and 10 samples per fingerprint. Four of such sessions were carried out.
- **Fine-grained longitudinal measurements**, where the signal strength was acquired every 10 meters for a section of 280 meters, using two terminals simultaneously. 30 samples were collected for each fingerprint and two sessions were carried out.
- **Fixed location measurements**, where 150 samples of the signal strength were collected at the same position to account for variations depending on the measurement conditions.
- **Radial measurements**, with fingerprints taken every 10 cm for a distance of 1.10 m between the wall and the LHC machine, at 50cm from the ground, 1000 samples per fingerprint. Three devices were used in parallel for data collection.

After characterizing the RSSI profile of the GSM network, a longitudinal assessment of the RSSI evolution for WLAN 802.11 was also performed, which allows us to compare and draw some conclusions on the differences.

4.2.3 RSSI ACCORDING TO POSITION

Among the most important characteristics of the Leaky-feeder cable is its low longitudinal attenuation. Therefore two experiments on assessing the RSSI along the cable were performed, having different step sizes: 40m and 10m.

In the first set of measurements (Pereira, et al., 2011), as we go along the tunnel we notice that the received signal strength can change significantly. In Figure 20, the mean and standard deviation of the RSSI values are shown as a function of the distance for the two most indicative sessions. We can clearly see two dominant GSM channels and traces of several channels from nearby tunnel sections. In the plot we can also identify two distinct areas, specifically before and after 240 m. In fact, the leaky-feeder is injected a new GSM channel at this location. Until then the new frequency experiences high attenuation as it propagates through air. After that point the propagation occurs normally in the cable and, therefore, the attenuation is much lower. In this region, approximating the RSSI evolution to a linear function, we obtained

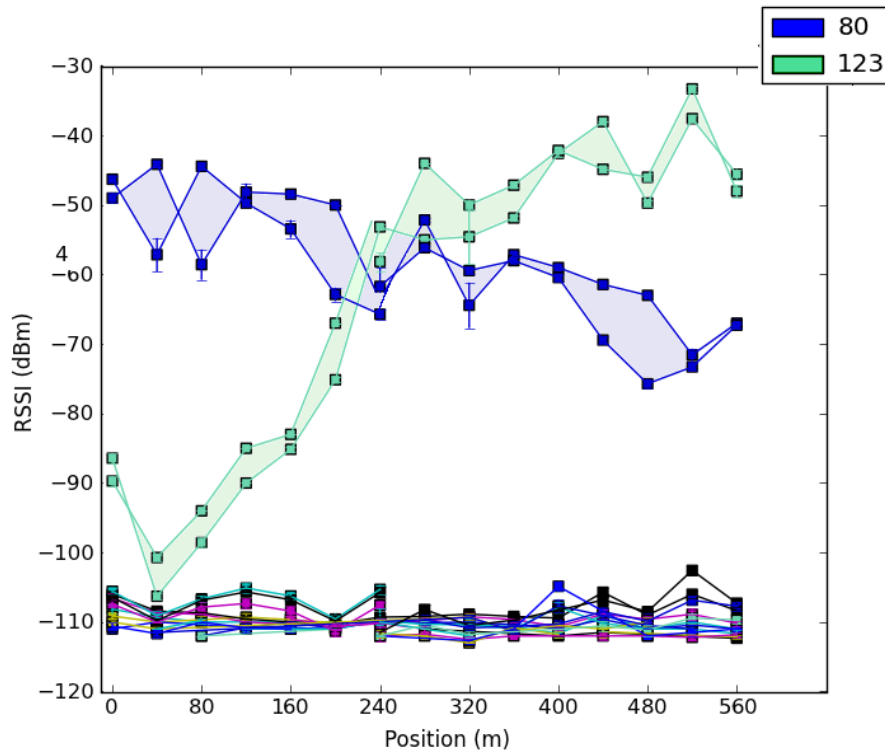


Figure 20 - RSSI evolution along the tunnel in a section of 600 m
Fingerprints were taken at every 40m. Each color represents a different channel, error bars represent standard deviation and shaded areas are delimited by the minimum and maximum RSSI values of the same frequency, obtained in different measurements sessions.

attenuation factors of 3.9 and 4.5 dB/km, slightly larger than the attenuation of the cable as in its specification.

Despite the fact that the cable's longitudinal attenuation introduces measurable signal changes, the variations in the RSSI values tend to obfuscate them. These effects are generally caused by the volatility of the measurement conditions but are also due to the influence of multipath propagation in the tunnel and multicoupling in the leaky-feeder itself (Weber, et al., 2010).

In order to better assess this effect, measurements were performed with a significantly smaller step, 10 meters, in a nearby region of the tunnel (Pereira, et al., 2012). Figure 21 presents the result of such measurements, as captured by two mobiles simultaneously, and shows many interesting aspects. In the first place one can notice that, in this region, a third channel can be observed and its RSSI well characterized. This fact shows that in some regions of the tunnel, the interconnections of the leaky feeder actually allow the nearby signal to pass through, creating a third usable GSM channel. Although not very strong, the additional channel is, where available, certainly an additional valuable resource for RSSI fingerprinting. Another very important point is that, even though two terminals were used per session and installed less than 10 cm apart, the RSSI values assessed by them always exhibit some discrepancy, to the point that, looking at the plot, it is not possible to say which two RSSI lines belong to the same session. From this observation we can conclude that the exact position of the receivers greatly influences its captured RSSI. Furthermore such discrepancies are mostly independent for each channel.

4.2.4 INTER-CHANNEL RSSI DIFFERENTIAL

In a network configuration like the one presented, several channels propagate over a leaky-feeder cable. Along these cables the various channels suffer a certain level of attenuation, depending on the cable characteristics, the distance travelled by the signal and the signal's frequency. This property normally characterized for each cable in terms of an attenuation coefficient stated in dB/100m for a given set of frequencies. Assuming the factor is constant all along the cable, the same level of attenuation should be found in all the channels when moving from one position to another. Even though the measurement conditions are likely to change slightly (for instance due to self-shadowing of the person conducting the measurement, changing body postures, different configuration and operational state of the accelerator equipment, etc...) they would affect the channels the same way. In this scenario if two channels were injected from

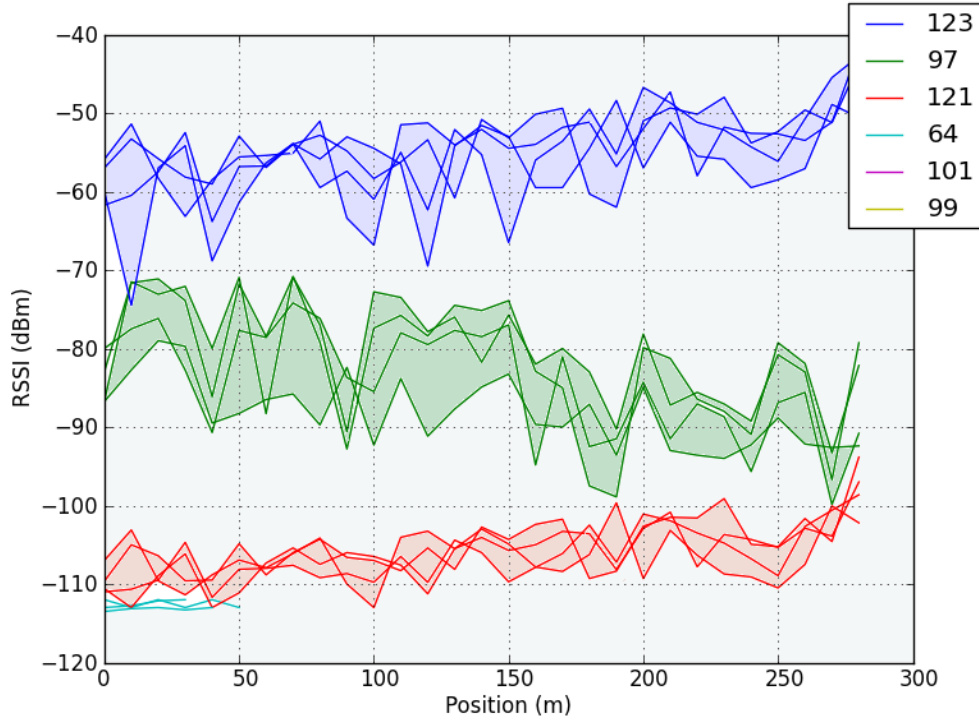


Figure 21 - RSSI evolution along the tunnel with fingerprints collected every 10m. Each channel displays four lines, as two mobiles were used and two identical sessions carried out.

opposite directions, the RSSI difference between these channels would be changing twice as much as the cable attenuation and, most importantly, this difference would be very robust against different measurement conditions. Unfortunately this effect hasn't been observed in channels propagating in opposite direction.

However, the last presented measurements opportunely captured data of an additional GSM channel and provide strong evidence that two channels propagating in the same direction indeed suffer the same RSSI oscillation levels independently of the measurement conditions. (Pereira, et al., 2012). Previous measurement didn't capture this effect since a third channel can only be found with sufficient strength in certain regions of the tunnel. Therefore, the location algorithm will consider this information as optional and, whenever possible, take advantage of it to increase the accuracy. Figure 21 shows the RSSI evolution for the GSM network along the tunnel section, in which one can clearly see the two dominant channels (ID 123 getting stronger and ID 97 attenuating) and a third weaker channel, also getting stronger.

Despite the large RSSI region for each channel, there is a noticeable similarity of their shapes between channel 123 and 121, which was not observed for channel 97 and any of the others. This fact motivated further analysis of this pattern and its inherent correlation.

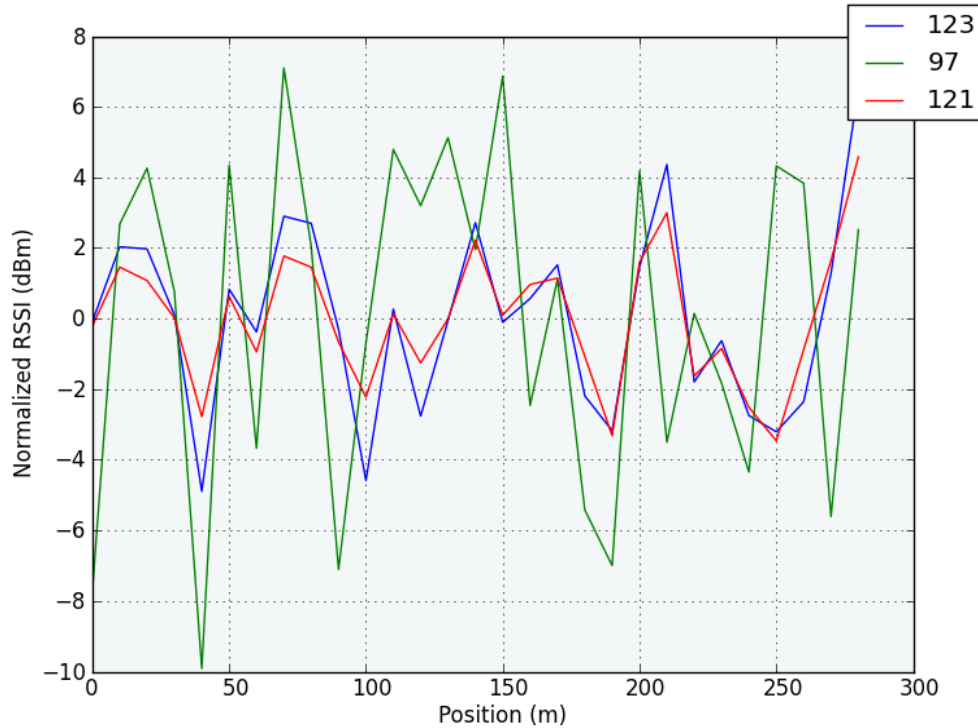


Figure 22 - Normalized GSM RSSI
Results obtained after filtering by the median and subtracting the linear attenuation coefficients.

In order to analyze the visually perceived correlation of some of the channels' RSSI in more detail, some statistical pre-filtering of the data was performed (Pereira, et al., 2012). In the first place the various RSSI per channel and position were condensed into a single value by calculating the median over the samples collected during one measurement session. Subsequently, the results were normalized by subtracting the linear attenuation coefficient obtained by least-square regression (Figure 22). It was found that the approximated attenuation coefficients (see Table 5) correspond very well to the value of the cable stated in its datasheet (RFS World, 2010).

TABLE 5 - APPROXIMATED LINEAR ATTENUATION COEFFICIENTS
OBTAINED FROM THE MEASUREMENTS OF DIFFERENT GSM CHANNELS.

Channel	Slope (db/100m)	Offset (dBm)
Channel 123	2.95	-58.29
Chanel 97	-4.58	-76.35
Channel 121	2.29	-108.93

TABLE 6 - CORRELATION COEFFICIENTS AMONG THE CHANNELS
CALCULATED PER MEASUREMENT SESSION AND MOBILE

Correlation coefficients per session		Spearman rank-order coefficient	Root-mean sq. deviation
Channels 123 & 121	Session 1.1	0.976	1.845
	Session 1.2	0.978	1.755
	Session 2.1	0.963	2.269
	Session 2.2	0.971	1.951
Channels 123 & 97	Session 1.1	0.720	6.260
	Session 1.2	0.689	6.601
	Session 2.1	0.660	6.896
	Session 2.2	0.848	4.586

Finally Spearman's rank order coefficient and the Root mean squared deviation were used to quantify the actual level of similarity. The correlation among the channels has been studied for each measurement session individually as shown in Table 6.

As can be seen, significant correlation exists generally between the channels 121 & 123, whereas lower dependence and larger deviations can be observed between the channels 97 & 123. The correlation is even more noticeable if the data of the different measurement sessions are not considered individually but combined - Figure 22 - which yields a Spearman rank-order coefficient of 0.99 and a root-mean square deviation of 0.92.

Therefore, the RSSI differential of these channels can be considered as a quite robust characteristic of a given location, which might then be leveraged for location finding. Hereafter, this measure is designated as the Inter Channel RSSI Differential (ICRD), which for the case of two channels whose signal propagates in the same direction, is defined as Same-Propagation-Direction ICRD (SPD-ICRD).

4.2.5 RSSI DEPENDENCE UPON MEASUREMENT CONDITIONS

Although the four detailed measurement sessions were performed in rather similar conditions, the observed RSSI values at each point exhibit divergent behaviors. It was interesting how one can have almost null variance in two consecutive measurements while their average differs by more than 10 dB (e.g.: measurement at 480m in Figure 20).

This fact motivated the stationary measurements (Pereira, et al., 2011) in where we tested three slightly different conditions:

- **Optimal:** We ensured no one was close to the equipment during the measurement process, by at least 30 meters.
- **Sub-optimal:** At least one person was standing beside the equipment during the measurement
- **Realistic:** One person was holding the equipment and slightly moving it during the measurement.

Each measurement point counts 10 samples, and their mean and deviation calculated.

Figure 23 shows the RSSI evolution for the measurements under the different conditions. For the two dominant channels, 80 and 123, the more adverse conditions the higher the variations and the averaged RSSI values tend to drop. Such observations are clearly confirmed by their respective histograms (Figure 24), where one clearly notices a larger spread of the distribution as well as a small shift to the left.

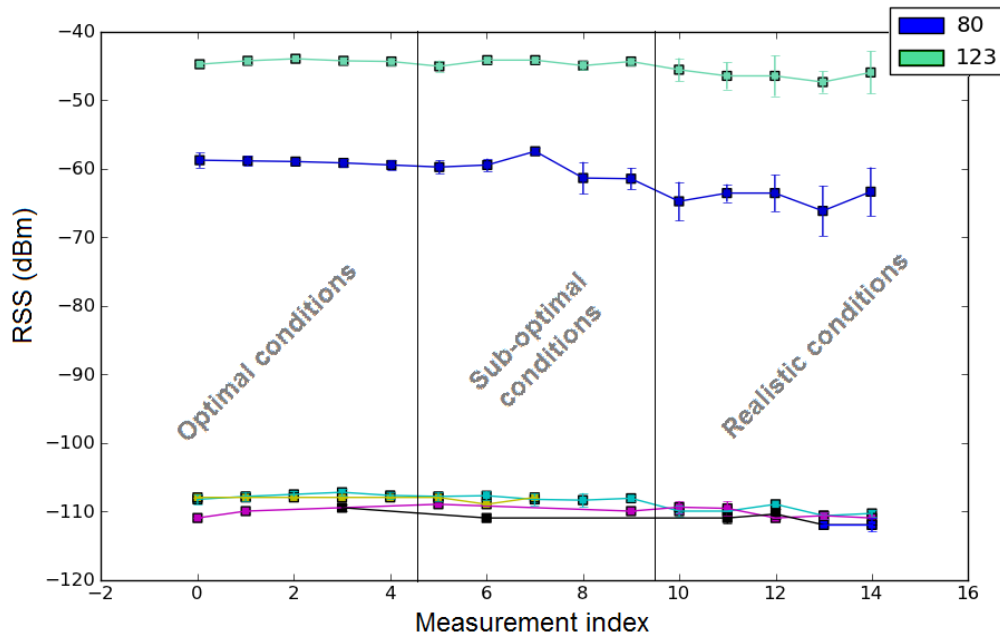


Figure 23 - RSSI dependence on measurement conditions.
Each group was taken with slightly different conditions, being a) Optimal, b) Sub-optimal or c) Realistic.

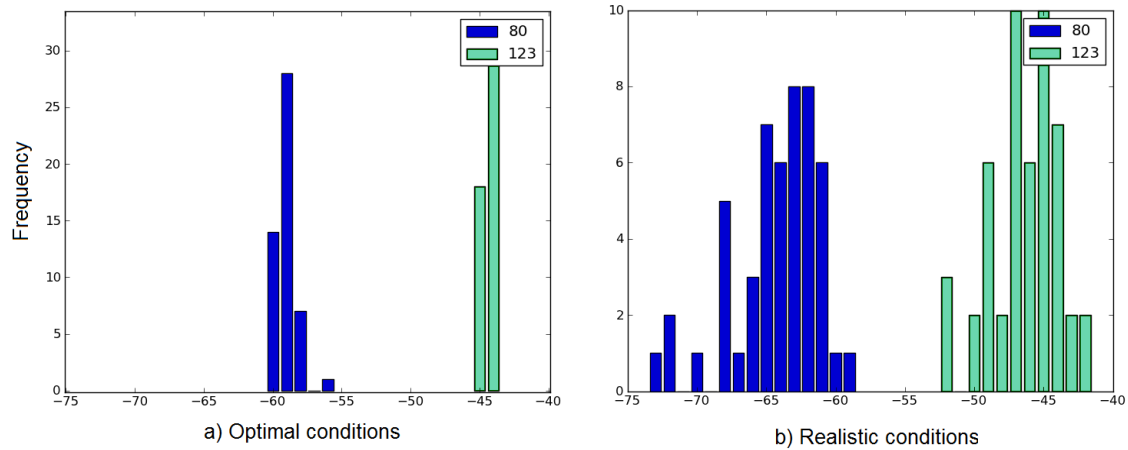


Figure 24 - RSSI histograms for two distinct measurement conditions

Evolution of the RSSI profile over a long period of time

In order to have a better perception on time changing conditions, another test was performed where samples were continuously taken in optimal conditions for approximately half an hour. Samples were then averaged in groups of 10 and their deviation respectively calculated. The results are presented in Figure 25, where one can easily identify the dominant and several nearby channels, all exhibiting a very constant profile during the experiment time. The only exceptions are the first and last points, which suffered the influence of a nearby person operating the device.

The results of the stationary measurements provide us clear insight of the existing background noise conditions. They support the hypothesis that the environment characteristics of this underground tunnel, under optimal conditions, are static enough to cause very little signal fluctuations, which is quite favorable for fingerprinting methods. However, for scenarios requiring some manual handling of the equipment, as it will be the case for radiation surveys, we must account for significant signal variations.

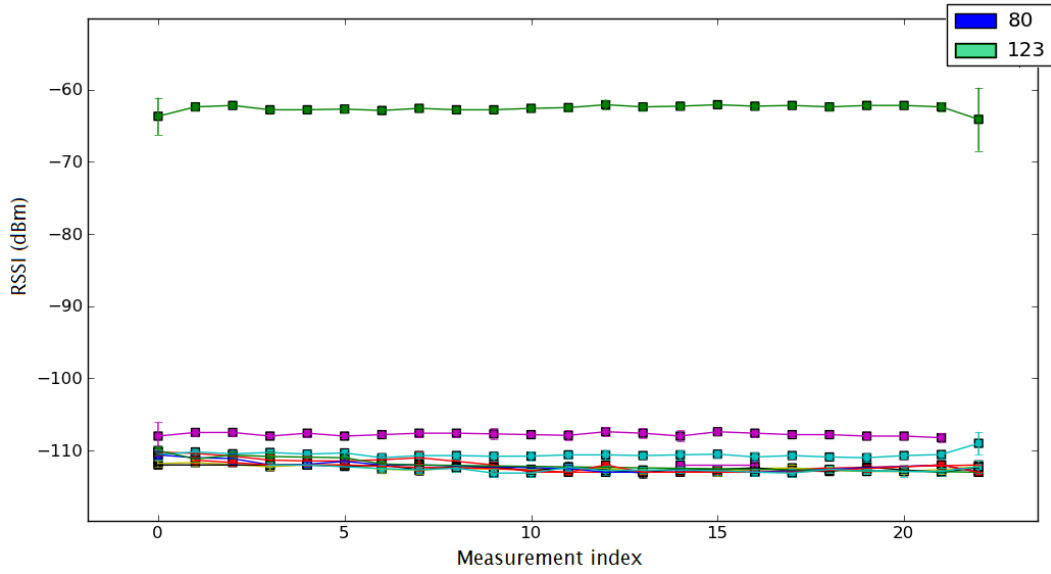


Figure 25 - RSSI profile evaluated for a period of nearly 30 minutes.
Both the dominant and detected nearby channels RSSIs are kept very constant over time.

4.2.6 RADIAL MEASUREMENTS

According to some studies available in the literature, even though the RSSI is more stable using Leaky-Feeder cables than with regular access points, significant signal variations occur due to fast fading and eventual presence of obstacles. To better account for these effects in the underground GSM network, a set of samples was taken in the same longitudinal position but slightly changing the distance to the cable, as specified in section 4.2.2.

Having a step of 10 cm, the attenuation due to space propagation can be considered as negligible. The RSSI variations therefore depend mostly on the fast-fading and self-coupling effects, and the results are very expressive, as shown in Figure 26.

Even though the RSSI values at each measured point were quite constant over time (note that the standard deviation bars for each point are almost invisible), they showed significant dependence on small scale location changes. If one considers all the measurements for each device and channel, i.e., each line in the plot, the overall distribution is found to be quite large.

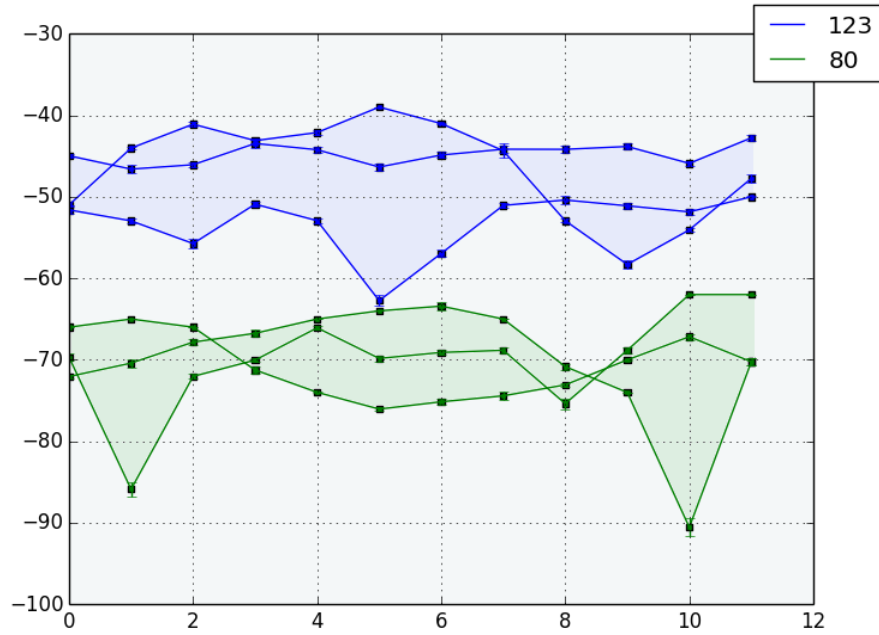


Figure 26 - RSSI measurements in different distances to the *leaky-feeder* cable. Each line represents the evolution of the RSSI along a ground line of 110 cm perpendicular to the cable, as captured by each of the three GSM units which could collect both channels simultaneously.

To minimize these effects, it is important that calibration samples are all taken in the same exact locations and line-of-sight (LoS) propagation is available and dominant.

4.3 RSSI CHARACTERIZATION WITH WLAN 802.11B/G

In order to compare results and understand to which extent the RSSI profile depends on signal frequency, a longitudinal test was also performed for Wireless LAN (IEEE 802.11 b/g) (Pereira, et al., 2012).

4.3.1 EXPERIMENT SETUP

For the experiment, two consumer-grade Access Points (AP) were installed in both ends of the 280 m section of the tunnel, the same region used for the fine-grained longitudinal GSM

measurements. Each AP is based on the Realtek 8187L chipset equipped with a high-gain (9 dBi) omnidirectional antenna. As illustrated by Figure 27, the APs were installed 150 m from each other and their antennas placed in parallel to the leaky feeder at a distance between 5 and 10 cm. This configuration promoted the injection and propagation of WLAN signal through the cable instead of direct connection. Furthermore, LOS conditions between the transmitters and the receiver unit were reduced by installing a reflexive shield, made out aluminum foil, near the APs.

Four measurement sessions were executed, in which the RSSI fingerprints were collected at identical positions as those from GSM, every 10 m, each one counting 100 samples.

Each AP provided its own channel, being used channel 1 (2.412 GHz) and 9 (2.452 GHz) on the left and right APs respectively. They were programmed to send beacon frames every 30 ms, which were then captured, parsed and stored by a mobile unit in common RSSI database. This configuration also allowed for the subsequent processing of the data by the different algorithms, independently of the data-source.

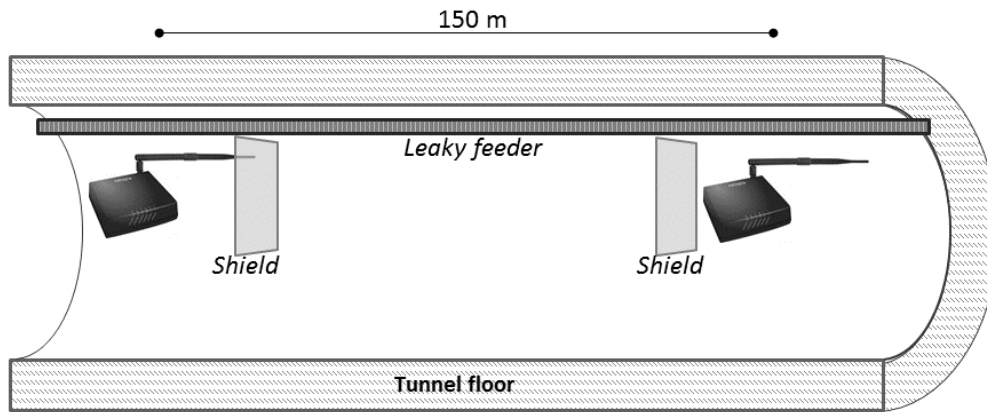


Figure 27 - WLAN experiment setup.
The shields avoid LoS conditions and the position of the antennas promote signal injection in the leaky-feeder cable.

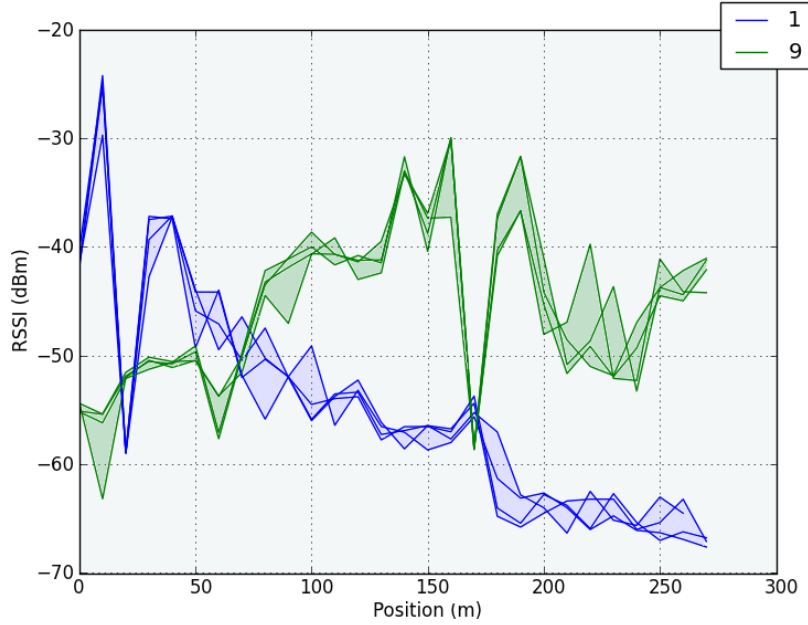


Figure 28 - WLAN RSSI evolution for two different channels.
The four lines for each channel represent the four independent measurement sessions carried out.

4.3.2 RSSI PROFILE

The results are shown in Figure 28. One can see the two WLAN channels, each coming from a different AP, and the RSSI plot reveals a much higher level of attenuation in comparison to GSM, in the order of 14 dB/100m. Such difference in attenuation comes as a direct consequence of the higher frequencies used. While at 900MHz the leaky-feeder provides a 3.16 dB/100m attenuation figure, at 2.4 GHz it would be expected to be higher than 10 dB/100m since, at the closest defined frequency - 1900MHz - the cable specification claims an attenuation of 8.52 dB/100m. This fact generally favors the performance of fingerprinting-based methods, as the points exhibit more distance among them and therefore are easier to identify. A deeper analysis on the achievable performance according to the *radio-map* characteristics is investigated by (Beder, et al., 2011). The experimental results and its analysis for the current scenario are presented in Chapter 5.

4.4 CONCLUSIONS

The characterization of the GSM and WLAN signals' power in the tunnel is an essential step in understanding, in the first place, the opportunities and challenges for fingerprinting techniques with RSSI measurements. In a network configuration as presented, where the signal propagates through leaky-feeder cable, the attenuation of the power is expected to be considerably lower than in the case of free-space-loss communication.

By analyzing the RSSI profile of the existing GSM network, it was found that the measured longitudinal attenuation ratios conform to the specification of the cable, i.e., in the order of 3 dB/100m. Nevertheless, at such low attenuation factors, the small power disturbances and fluctuations due to fast-fading, reflections and obstacles (including the measurement device itself), found to be up to 10 dB, can easily obfuscate the signal attenuation introduced by the cable. From this fact one can draw the conclusion that RSSI localization with resource to analytical methods is very limited. Indeed, according to the free-space model, distance errors would be proportional to the ratio between the RSSI fluctuations and the cable's attenuation, i.e., in the order of 300 meters.

In turn, being an empirical method, fingerprinting can explore other properties of the measurements for uniqueness search and location matching. For that a more detailed scan was performed and a third GSM channel was found. Since two of those channels had follow the same propagation direction, their pattern was further analyzed and interestingly found to very similar among them, up to a 99% spearman rank-order coefficient. From this observation, the same-propagation-direction inter-channel RSSI differential (SPD-ICRD) seems fairly resilient to signal power disturbances and fluctuations.

However fingerprinting methods are also bound to the validity of the *radio-map*, which can be assessed with the reproducibility of the measurements. In order to evaluate that, several sessions, accounting for similar and slightly different measurement conditions, were performed. From the longitudinal measurements, where several collection sessions were carried out under similar conditions, one can see that some significant differences arise at some points – see for instance the region of channel 97 in Figure 21. This fact raised the interest on what could be affecting the RSSI to that extent. Therefore further tests were conducted analyzing the effects of the measurement conditions and differences in the distance to the cable. The results are very expressive, showing that these factors have a very strong impact on the measurements: under realistic conditions, where the measurement device is moved slowly by a person operating it, a

much larger RSSI distribution appears and the mean value drops by 2 to 4 dB's; additionally, when slightly moving the measurement device away from the leaky-feeder, the RSSI variations are very considerable, exhibiting deltas of more than 20 dB's.

The tests characterizing the GSM signal on the LHC tunnel deployed over leaky-feeder cable provide a very good insight on the power variation according to the longitudinal position, but also on its behavior when subject to different measurement conditions and distance to cable. It is experimentally shown that, although the longitudinal attenuation stays within the cable specification, the signals' RSSI is heavily affected when testing for the change of conditions. Although the reason behind such acute sensitivity is not completely understood, we do believe that the metallic outer shell of the magnets and the presence of large metallic information panels on the walls and on the magnets' shells highly contribute to the creation of complex reflection fields, exhibiting non-uniform power patterns. Unfortunately a detailed study of these conditions would require changes to the current environment which are not possible.

Furthermore, in order to check for technology dependence, experiments with WLAN were carried out in which two AP's create two channels and promote their propagation over the leaky-feeder cable. The experiments shows that a much higher attenuation occurs longitudinally, in the order of 14 dB/100m, and that differences arising among independent measurement sessions are much narrower than in GSM, usually lower than 3 dB's. This fact further emphasizes that GSM frequencies are especially more sensitive to interference and, therefore, their performance with fingerprinting for location purposes may reasonably be inferior.

PROPOSED RSSI FINGERPRINTING METHODS AND PERFORMANCE EVALUATION

After the characterization of the RSSI profile in the tunnel, an additional phase was taken for the development and test of new fingerprinting algorithms, taking into account the observed signal characteristics. We start by analyzing the raw performance of several distance metrics, then a new distance metric is tested, and tests using GSM and WLAN are performed.

The performance is assessed via a new software utility which, using a dedicated set of samples from the *radio-map*, computes the algorithms' ranking and their accuracy level in realistic conditions. In the last part of the chapter some considerations on the achieved performance levels and their limits are provided.

5.1 EXPERIMENTS SETUP

In order to evaluate the performance of fingerprinting methods for the current environment several points had to be addressed. First, it would be of utmost importance to make the tests in realistic conditions, so that the measured performance levels could reflect those of the real work scenario of radiation surveying. Second, it would be necessary to design and implement a solution for automated test and benchmarking of the several location algorithms. Only with such a tool the algorithms' performance could be evaluated and compared among them, and their modifications and respective parameter tuning could incur a smaller penalty time due to the re-running of all the necessary tests. At last, it would be required to re-use some of the collected data, both GSM and WLAN RSSI, and store it to a common database. In this database data also had to be preprocessed, so that tests with large fingerprint count are (1) faster to execute and (2) mimic the real conditions in the case of a full tunnel fingerprint database. The experiment setup and the software tool implemented for the case are described next.

5.1.1 SETUP FOR OFFLINE PHASE

The offline phase can be resumed to the process of collecting the RSSI samples and store them to a database. The database can be of any format and indeed, in a first phase, the fingerprints were collected to text files which were then directly being used as an RSSI database. This format was enough for initial processing and plots extraction, used for instance in early stages of the RSSI characterization. Once it was understood that the amount of samples had to significantly increase and several algorithms would have to run fast over this data, this offline phase had to be optimized. Specifically two actions were taken:

1. Alignment of the tunnel characterization and fingerprinting evaluation activities, so that the measurements are taken with similar parameters, and even if coming from distinct network technologies, they can serve both purposes.
2. Collection, conversion of all the fingerprints into a common format and storage to an SQL database. For the conversion, storage and retrieval of the data several small tools started to be developed, which finally became part of the software framework described in the next subsection.

Fingerprinting methodology

In line with the fine-grained longitudinal measurements, the data used for fingerprinting performance evaluation was collected in a slightly curved tunnel sector over a length of 280 m. Fingerprints were taken every 10 m, yielding a total of 29 calibration points. Thirty samples per point were collected simultaneously by two mobile phones, and two complete subsequent sessions were performed. For the case of WLAN fingerprints, the same calibration locations were used, each counting 100 samples, with 4 independent sessions carried out.

Fingerprints statistical condensation

The fingerprinting calibration phase performed over large halls require the collection of thousands of RSSI samples. If not carefully addressed, all the data may become difficult to handle or, most importantly, severely impact on the performance of the online phase.

For instance, the raw fingerprinting files of the detailed longitudinal measurements (30 samples, 29 points, 280 m, 2 devices, 2 sessions) take nearly 500 kB. Even though the size might seem reasonable, they include over 80% overhead text and the parsing computational demand

to extract the useful data is very significant. Therefore it becomes unreasonable to use the raw files directly for the online phase, when all the fingerprints are required at once.

To overcome this problem and considerably reducing the database size, all the samples were processed per point and network technology and several statistical parameters describing each fingerprint were calculated:

- Minimum and maximum
- Quartiles
- Histogram, fenced at $1.5 \times \text{Inter-Quartile Range (IQR)}$ (Frigge, et al., 1989)
- Histogram high and low fence

By saving the histogram fenced according to the IQR, one significantly reduces the presence of outliers, while efficiently storing the samples RSSI information. Moreover, from these entries one can very easily obtain other statistical measures, like the median which is also the second quartile.

Since it is not common - and arguably worthless - for fingerprinting methods to operate directly on all the samples, statistical information is stored into the fingerprinting database and the RSSI samples optionally skipped. All the implemented online methods make use of statistical information only.

Fingerprinting database format

An SQL fingerprinting database was designed and implemented in SQLite so that they would be centralized and accessible in a standard way. Some additional tools were implemented to parse and save the RSSI data into this repository. For each measurement session, 3 database tables are created:

- *[calibration_id]_rssi* - A table containing all the raw RSSI samples, and eventually other information coming from the capture software, like channel noise estimation.

A typical GSM entry consists of the following fields:

[Session, Mobile, Point, Channel], Sample, Power, C1, C2

The first four fields - identifying the fingerprint - and the Sample field - identifying the sample number - are all integer, the Power, C1 and C2 fields are dB's stored as "floats".

session	mobile	point	channel	histogram_str
1	1	0	123	{-56: 5, -55: 8, -57: 7}
1	1	0	97	{-84: 5, -83: 9, -82: 6}

Figure 29 - Structure and example of histogram fingerprint representation

- *[calibration_id]_hist_fenced* - A table which contains the histogram, fenced at 1.5 IQR. The field is of string type, containing a JSON encoded representation of the histogram. The table structure and example data can be seen in Figure 29.
- *[calibration_id]_quartiles* - A table which contains the quartiles, their low and high fencing limits and also the minimum and maximum. The entries consist of the structure:
[Session, Mobile, Point, Channel], Q1, Q2, Q3, Q4, Min, Max, Min_fence, Max_fence

All fingerprints, either in raw or their histogram or quartiles representation, are identified by a four-field key [session#, device#, Point and Channel]. This indexing scheme is always kept, even for other networks or under single session tests, in order to keep the format standard across different tests and algorithms. Indeed, when parsing and writing to the database, or using the data in the online phase, it is enough the reference the *calibration_id* table prefix and the tools will write/fetch the required data to/from the correct place.

5.1.2 ONLINE PHASE: A SOFTWARE FRAMEWORK FOR RSSI FINGERPRINTING

Methodology

In the on-line phase, in order to assess the performance of the location algorithms with a reasonable confidence level, they were tested with independent sets of samples taken in addition to those used to create the *radio-map*. Ten random samples were taken from each group (identified by location, technology, receiver and channel) and used to represent an on-line fingerprint.

Each of these fingerprints is then evaluated against the *radio-map* fingerprints in the respective location. For example, in a configuration of 2 measurement sessions with 2 receiver units, one ends up with 4 online and 4 offline fingerprints for each point. The tests can then be specified to run against a specific *radio-map*, all *radio-maps* or a joint one built from all the

sessions together. The software framework implements this behavior and, for each test, several algorithms or even a combination of them can be benchmarked.

Despite testing each algorithm's performance, it would be interesting to compare the performance among all, or a large set, of them. For that purpose a global comparison script was prepared which, based on the localization framework, loads the *radio-map* and tests a set of algorithms and their parameters with all the stored online samples against the offline fingerprints. This script, called mass-test, requires the definition of the algorithms and their parameters returning, in the end, a summary with the methods' scores and accuracy measures. For instance, the following definition would make the script run with the algorithms "match_difs1", "match_difs2", "match_abs_values" and "match_hybrid" in slightly different configurations and return a global execution log, with benchmarking ranks and performance indicators. For a full execution log refer to Appendix A.

```
1. methods = [[match_difs1, {}],  
2.           [match_difs1, {'compare_first_only':True}],  
3.           [match_difs2, {}],  
4.           [match_abs_values, {}],  
5.           [match_difs2, {'consider_strong_link':True}],  
6.           [match_hybrid, {}],  
7.           [match_hybrid, {'consider_strong_link':True}] ]
```

This procedure finds its best application when testing hybrid algorithms and data fusion - section 5.2.3.

A location fingerprinting software framework

In order to simplify and automate the execution of the tests, a software framework for localization fingerprinting was implemented and named Easy Location Fingerprinting (ELF). The goal of the ELF framework, as its name suggests, is to help building fingerprinting programs by implementing the most common actions and creating an abstraction layer hiding the complexity of the fingerprinting database.

By design, the framework is flexible enough to work with any matching algorithm which respects the protocol. Among the numerous features, it allows for transparent handling of different data sets, can perform location fingerprinting and include tools to verify and process *radio-maps* and to evaluate/compare the performance of location fingerprinting algorithms.

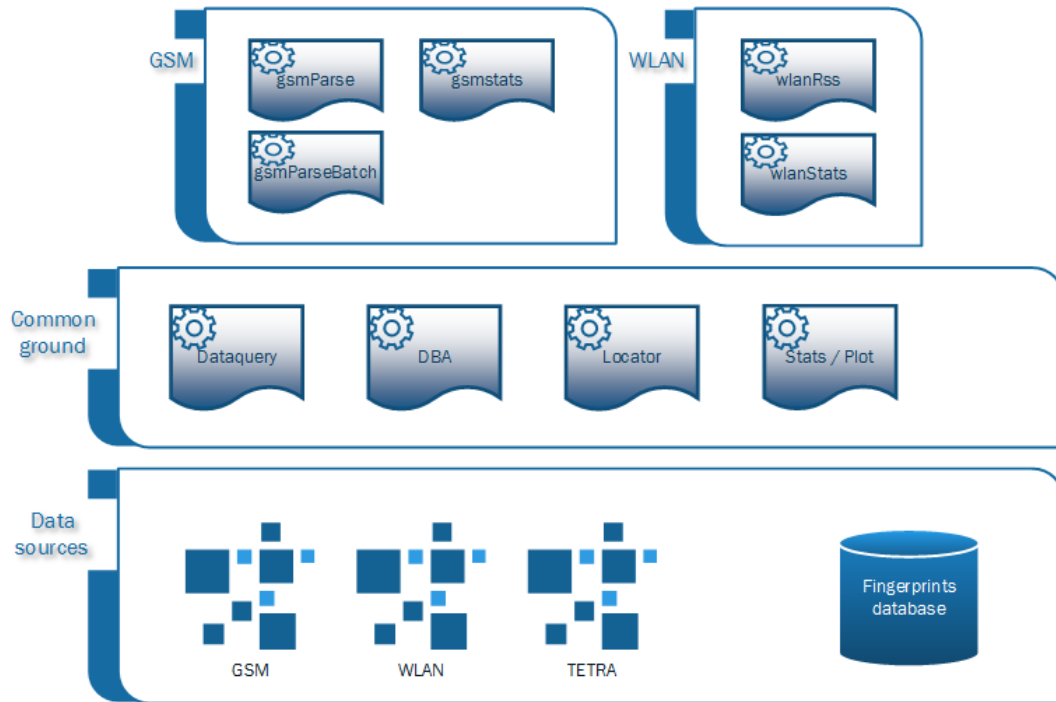


Figure 30 - Architecture of the Easy Location Fingerprinting framework

Design and modules

The framework was developed in Python which, besides allowing for rapid development cycles, has numerous libraries for scientific, numerical and statistical analysis, plotting, etc., among them SciPy, NumPy and matplotlib.

The ELF framework evolved as a set of independent scripts which were then merged and improved together. As a result, its modules are very loosely coupled and the architecture is kept simple, as illustrated by Figure 30. The architecture can be split in three layers, according to the components class, namely Data Sources, Common ground, and specialized (GSM and WLAN) functions. The Common Ground layer is the library core, where the most important modules, reside and are implement the technology independent principle. They are:

- **Dataquery** - This module is the main responsible for the handling of the fingerprinting data. It implements a data structure meeting demanding performance requirements and a manipulation API which mimics the SQL standard, and extends it to perform generic operations common to location fingerprinting, including:
 - ⇒ *Select* - Filters the current dataset, keeping only the specified fields.
 - ⇒ *Where* - Applies row-level filtering, returning only those which meet the conditions.

- ⇒ *Group_by* - Like in SQL, it groups data having the same values in the selected fields and reduces the groups to a single item using a specified function, like SUM.
 - ⇒ *Organize_by* - It groups data having the same values in the selected fields, without reducing. It can optionally create a nested data structure.
 - ⇒ *Get_group* - It returns a group from a nested data structure, whose indexing field values match those provided.
 - ⇒ *Flatten* - It transforms a nested data structure into a flat one.
 - ⇒ *Combine* - It allows for combining data from two sets which might be grouped, eventually performing reduce binary operations, like difference, sum, etc.
 - ⇒ *Order_by* - It orders a dataset by the specified fields, lowest to highest or reverse.
- **DBA** - This module implements an abstraction layer to the fingerprints database. It is responsible for the creation of the data tables given a dataset (*import2db* function), importing the generated statistics (*import_stats2db*) and data fetching (*table_select*). Data fetching with automatic table resolving is implemented in the Stats module, since it is the only kind of information required by the location algorithms.
 - **Locator** - The locator is the central module implementing location fingerprinting functions and defining the interface for integrating additional algorithms. This interface is explained in the next part - Interoperation protocols. The locator module includes the several proposed location finding methods and their required pattern matching algorithms, as well as evaluation routines for the algorithms - see “Approaches for performance evaluation of location fingerprinting algorithms” and also a template script for global testing. Among the implemented pattern matching algorithms, available in this module, there is *match_abs_values* for matching fingerprints based on their absolute RSSI, and *match_diffs* for matching fingerprints based on their differential RSSI (ICRD); a hybrid implementation (*match_hybrid*) and a customizable KNN algorithm. The algorithms are explained in part 5.2.
 - **Stats & Plotting** - Functions related to the statistical analysis of the fingerprinting data, allowing to (1) generate the required statistics from the raw RSSI values and store them in the database, (2) apply statistical transformations to a dataset, including histogram representation and (3) plot data coming from raw or statistics datasets and histograms. Due to their importance, the main functions/classes are mentioned here.
 - ⇒ *calc_stats* - Generates the fingerprinting statistics from raw RSSI samples, including the histogram fenced at 1.5 IQR and quartiles and stores them to the database.

- ⇒ *get_stats* - Obtains statistical information from the fingerprints database, about a point or a set of points, optionally (1) filtering by session and/or device, (2) merging the different sets with a given reduce function and (3) plotting after reducing each fingerprint's histogram to a value, using average by default.
- ⇒ *Histogram class* - Histogram class objects store a representation of a fingerprint, in histogram form and perform related operations on it. They can generate the histogram out of raw RSSI samples and can directly plot the data.
- ⇒ *plot_data* - a function dedicated to present series of data in a line plot. Multiple series are supported by providing them in an array, i.e. a nested dataset.

On top of the ELF common layer, specific layers exist for each technology. These layers provide utilities to parse data from the raw measurement files, as collected by the capture scripts, preview them in a plot and import them to the database. Since they have been implemented to meet the requirements of this specific project, they are not discussed in detail.

Interoperation protocols

Having in mind a decoupled design, where extensions can be easily integrated and combined, a protocol for extension modules was defined. This design is a key element for allowing the implementation of hybrid methods in a straightforward way.

The basic premise is that all location algorithms have to perform, in a first stage, some pattern matching between the online and the offline fingerprints. Generally, the similarity is expressed with any non-dimensional number, even though it is usually converted to a percentage. Localization algorithms can then take the most similar offline fingerprints and further process them, eventually interpolating, in order to obtain a final position.

In the case of the ELF framework, in order to allow for hybrid matching, the intermediate evaluation of the similarity between fingerprints is given in percentage, but additionally, the result of each matching routine must be a list of the most probable discrete locations having their similarity measures normalized, so that their sum is 100%. The result in this format can then be easily combined with the result of the same algorithm over different data representing the same location or even with the result of a different algorithm - see the Hybrid algorithm in section 5.2.3 for such a case and an example of the guesses list.

On a last stage, the algorithms can apply direct interpolation or filtering methods to a list in this format.

Approaches for performance evaluation of location fingerprinting algorithms

In order to evaluate the performance of location fingerprinting algorithms, two approaches were adopted: Ranking and Error-distance assessment. When ranking (or benchmarking) an algorithm, a score is computed based on all an assessment of the validity of all results, eventually including intermediate values. Even though a data set is required, the benchmarking shall be as data-independent as possible. The advantage of this method is that, if the score correctly reflects an algorithm quality, it can be used to optimize its parameters and improve its location finding effectiveness in a fast way, or even automatically to some extent. However, such methods evaluation are rather synthetic, since the yielded score is a mere relative value which has no meaning outside the current test conditions. Therefore, a score can only be used among the same - or very similar - algorithms, excluding hybrid and multi-stage variants.

The second approach evaluates the performance in terms of achieved accuracy or error distance. This is the most common performance evaluation found in literature, mostly due to its output being intelligible and globally comparable. However, one must be aware that they are dependent on the data set and, therefore, an algorithm X performing better than Y in scenario Z1 doesn't necessarily mean that X is better than Y and is going to perform better in scenario Z2. For that reason, for the implemented KNN variants, besides the *ranking*, performance was also evaluated in terms of the actual error-distance, with K=1, 3, 5 and 7. The output of a complete comparative session, employing both ranking and error-distance assessment is provided in Appendix A.

The Scorecard ranking method

As discussed before, algorithms in the framework return, for each fingerprint, a list of their found most probable positions (the guesses) and their corresponding confidence level. The Scorecard ranking takes advantage of the *a-priori* knowledge of the actual position of the fingerprints and computes a score according to the guess rank order of the point in the list (k), the calculated probability (P) and the distance Δ to the actual position. Specifically, the weight assigned to a specific guess lowers in geometrical proportion to the distance-index and to the guess order (see Figure 31). The ranking is performed for the whole data-set (N location fingerprints) and for the 5 most probable points for each fingerprint, according to:

$$R = \frac{1}{N} \sum_{i=0}^N \sum_{k=1}^5 \frac{S_{i,k}}{2^{\Delta_i} \cdot 2^k} \quad (\text{eq. 5.1})$$

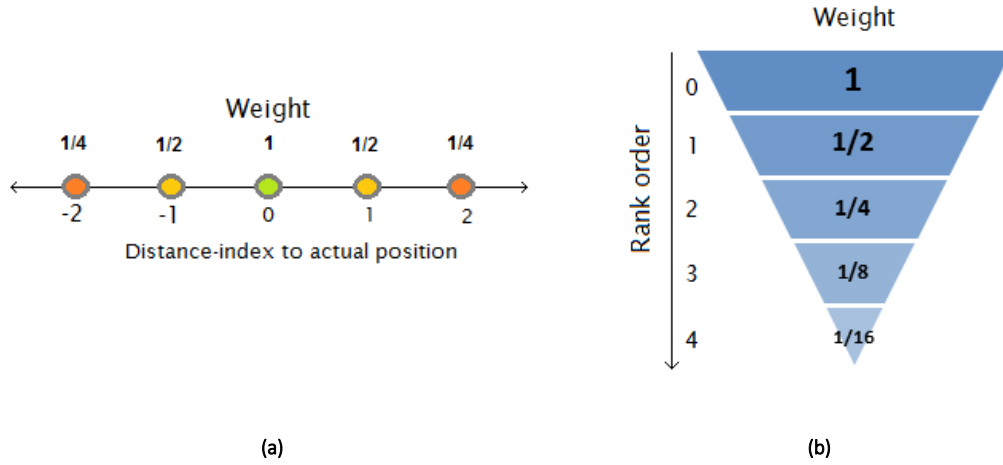


Figure 31 - Scorecard ranking method.

The weighting is performed (a) according to the distance-index between the guessed and the actual position fingerprint position and (b) according to the guess rank order.

This method accepts contributions until the 5th most probable guess to allow the best score to be achieved when the correct point and the four closest neighbors are given the highest probability in the right order. By applying (eq. 5.1) the ideal method with ideal data would be given 1 for every sample and therefore, by applying a factor of $1/N$, the method's score is bounded effectively to 100%.

The Accuracy-histogram ranking method

Another ranking method that was quite useful in showing deeper information of the matching algorithms was Accuracy-histogram. In this method, given the list of the guesses and their confidences, a histogram would be generated in which the bins represent the rank order of correct guess. In such a representation, the more left skewed the histogram gets the better, as it means more correct positions are being ranked higher against other positions. As an example, consider a test consisting of 10 online fingerprints against the *radio-map*. Of those 10, 5 generate guess lists having the correct position placed in their top, 3 will generate lists having the correct position in the second place, and the last two find the correct position in third place. This generates a histogram having values 5, 3, 2 for bins 0, 1, 2 respectively. The global benchmark is then calculated, as the sum of the first three bins weighted by the inverse of the bin number, as:

$$R = \sum_{b=0}^2 \frac{H_b}{2^b} \quad (\text{eq. 5.2})$$

5.2 PROPOSED LOCALIZATION ALGORITHMS

Among the location fingerprinting algorithms, those based on the k-Nearest-Neighbor are particularly interesting due to their relative simplicity to implement, flexibility to incorporate new pattern matching methods and the fact that they generally perform very well even when compared to other - usually more complex - algorithms. Their performance was found to be alongside with other deterministic and probabilistic approaches (Honkavirta, et al., 2009), or even superior, when compared for instance to Artificial Neural Networks (Lin & Lin, 2005).

The developed location fingerprinting algorithms are therefore based in KNN, having their pattern matching routines and parameters customized to meet the characteristics of the experiment.

5.2.1 MODIFIED GENERAL-PURPOSE WEIGHTED KNN

In weighted-KNN approaches, additional information is taken into account when evaluating the matching of an online and an offline fingerprint. These additional factors are translated into weights, which are applied to the distance between the points (eq. 2.20).

A new weighting method accounting for fingerprint measurement conditions

In the scenario of the LHC tunnel, as observed in the previous part, the measurements can be quite stable as long as they were collected in optimal conditions (Figure 23). When the conditions start to be less ideal, the fingerprints distributions' get larger and their means and medians are less reliable.

To introduce that factor in the computation of the fingerprints distance a new weighting method was investigated. This method builds on the following premises:

- The narrower the fingerprint distribution the better it represents the RSSI and the more reliable it is.
- A wider distribution means there is more uncertainty, as opposed to dissimilarity, and therefore a good fingerprint agreement shall not directly be negatively weighted.
- Considering fingerprints whose mean values are "N" dB apart, there's better agreement if both present large distributions which partially overlap, than narrow distributions which completely separate.

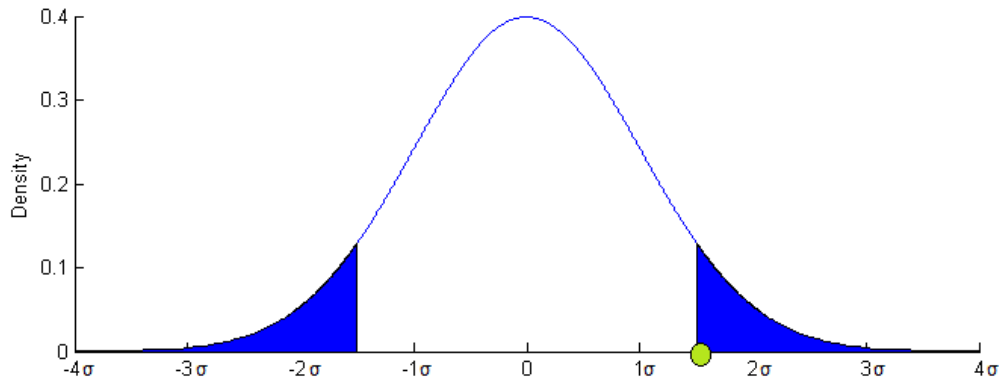


Figure 32 - Weighting according to the CDF approximate

These premises lead to the implementation of a weighting method which considers the overlapping between the online and offline fingerprint distributions. The method calculates the weight, per bin, as the probability density sitting outside the bin normalized distance - see Figure 32.

Implementation

As an initial step, a generic KNN fingerprinting algorithm was implemented which could be highly parametrized. This flexibility allowed the test and optimization of the several parameters with the existing *radio-map*.

Equations (eq. 2.16) and (eq. 2.20) are the foundation for a generic KNN algorithm. From their analysis one can see that can be implemented in software in a simple way while leaving the parameters openly configurable. Furthermore, if one keeps the separation of the roles, as suggested by the two separate equations, one can formulate a localization algorithm as having in its base a fingerprinting matching method (e.g. a distance-norm measurement as in (eq. 2.16)), followed by a location estimation phase, like KNN as in (eq. 2.20). The first approach was nevertheless to implement KNN as a direct translation of these equations, as shown in the following two code blocks, respectively.


```

1. def distance( x, y, norm=2 ):
2.     assert len(x) == len(y)
3.
4.     abs_deviation = 0.;
5.     for i, xi in enumerate(x):
6.         abs_deviation += abs( (xi-y[i])**norm )
7.
8.     return math.pow( abs_deviation, 1.0/norm )

```

```

1. def knn_average( k_results, k=5 ):
2.     if not k_results: return -1.
3.     k_results = k_results[:k]
4.     return numpy.average( column(k_results,0), weights=column(k_results,2) )

```

These two code excerpts define the algorithm. Nevertheless, some glue logic is necessary to evaluate the online fingerprint across all the *radio-map* and then order and normalize the distances to the common format. The implementation of such routine can be found in Appendix B.

In the implementation of the new weighting method, the offline fingerprint distributions were approximated to a Gaussian and, for each bin of the online fingerprint histogram, the distance was calculated and weighted by outside the area, as mentioned. The approximation to a reference distribution allows to simple computation of the outside area from its known Cumulative Distribution Function (CDF). Since the Gaussian CDF function cannot be analytically obtained, its values are usually taken from the equivalent, and computationally known, error functions (erf), as:

$$P\left(x > \frac{x_0 - \mu}{\sigma}\right) = \text{CDF}(z) \xrightarrow{\text{numerical}} Q(z) = \frac{1}{2} \text{erfc}\left(\frac{z}{\sqrt{2}}\right) \quad (\text{eq. 5.3})$$

$$W = \text{erfc}\left(\frac{z}{\sqrt{2}}\right), \quad z = \frac{x_0 - \mu}{\sigma} \quad (\text{eq. 5.4})$$

Since we want the two side lobes of the CDF, the $\frac{1}{2}$ factor in (eq. 5.3) disappears and, according to (eq. 5.4), the weight is calculated directly from the erfc function, whose only argument is the normalized fingerprints distance divided by $\sqrt{2}$.

This method is graphically represented in Figure 32, where the bin of the collected fingerprint (green mark) deviates 1.5σ from the mean RSSI in the *radio-map*, which yields $W=0.13$.

TABLE 7 - PARAMETERS OF THE KNN BASE IMPLEMENTATION

Parameters	RSSI grouping function	Distance measurement norm	Weighting method
Parameters' values	Average	Manhattan (1-norm)	No weighting
			Weighted by CDF
	Maximum	Euclidean (2-norm)	Weighted by σ^2
			Weighted by σ

Parameters and methodology for variants evaluation

Since it is difficult to predict which norm will provide the best performance, and what are the best weighting and RSSI grouping functions, a series of methods variants were defined.

Regarding the norm, both Manhattan and Euclidian norms were tested. In case of a missing channel, either in the sample or in the *radio-map* point, the device's sensitivity threshold -115 dB is assumed. Each difference is additionally weighted by one out of three methods, trying to take advantage of the standard deviation: in the simplest case $W = 1/\sigma$ and $W=1/\sigma^2$ which are compared against the new weighting method previously described. For base comparison, tests without weighting were also included. Another factor analyzed was the impact of using the maximum of an online fingerprint, to represent it, as opposed to its average. Although questionable, it was not excluded the possibility of the stronger samples in the fingerprint to be more meaningful. To summarize, the variants of the method result from the combination of the following parameters: fingerprint reduce function, distance norm and weighting method - see Table 7.

Finally, in order to compare the 16 variants and evaluate which one would perform better, the ScoreCard ranking method was used along with the data collected in the detailed measurements. It takes all the bins (600 samples) collected during the *detailed measurements* (section 4.2.3) and processes them against all *radio-maps*, except the one they belong to, i.e. three out of the four maps - a technique similar to that described in (Otsason, et al., 2005).

Benchmarks

The full results from the ScoreCard evaluation can be found in Appendix A. In these tests, all the variants using the average as the grouping function for the offline fingerprints outperformed those using the maximum by a factor between 0.5% and 8%. It is therefore clear

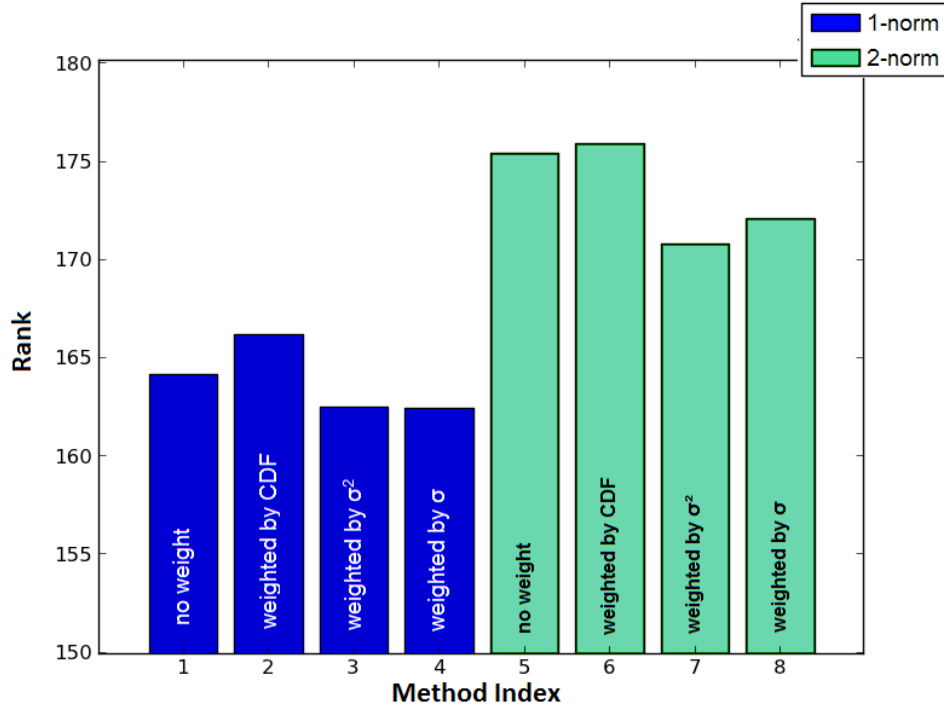


Figure 33 - Benchmarking results of the several w-KNN variants.

The bars represent the score of the methods with different weightings and norms, calculated with 600 samples

that, even though the lower-magnitude samples might be less important, some high-magnitude samples might also be non-realistic or statistical fluctuations, due to some noise in the monitoring device or signal self-interference.

The impact of the different distance measurement norms and weighting methods of the remaining eight variants, as captured by the ranking algorithm, is resumed in Figure 33. It is observed that the Euclidean norm is better suited to this case, allowing for a better assessment of the similarity of the fingerprints, and yield a score 8% higher in average. From the weighting point of view, the best results were obtained by weighting the distance by the normally approximated CDF of the offline fingerprint, followed by no weighting. Surprisingly, the latter performed reasonably well although it didn't make any use of the standard deviation. In turn, the methods directly using the standard deviation clearly didn't take the best advantage of it, which indicates that fingerprints having a larger standard deviation shall not be directly penalized against the other fingerprints.

To summarize, the best method has the following characteristics: 1) it uses a *radio-map* whose calibration points were averaged; 2) the error distances are measured by the Euclidean

norm; 3) the error distances are weighted by the CDF of the normally approximated power distribution.

In the subsequent experimental section, the method is applied to a real *radio-map* and accuracy figures in terms of real distances are provided.

5.2.2 ICRD-AWARE ALGORITHM FOR FINGERPRINTING USING LEAKY-FEEDERS

Following the findings reported in section 4.2.4, a second algorithm was developed which takes advantage of the RSSI difference among different channels, here denominated Inter-Channel-RSSI-Differential (ICRD). This is motivated by the fact that small changes in position might affect all channels similarly, but their relative power will remain constant and might reflect the position RSSI profile more accurately. In the case of channels propagating in the same direction, it has been observed that they actually correlate very closely and therefore these channels, denominated Same-Propagation-Direction ICRD (SPD-ICRD), are considered independently.

Basically, after an initial step of identifying the channels common with the on-line fingerprint, the algorithm acting on the ICRD map works by calculating the differential between the channels in a circular order. For instance, if there are four common channels, e.g. channel 1, 2, 3 and 4, then only the differentials 1-2, 2-3, 3-4, 4-1 are used. This technique was motivated by the fact that all-to-all channel comparison could easily become computational prohibitive. Moreover, due to the circular link, absolute RSSI changes in any channel will always affect only two differentials independently of the total number of channels found in the *radio-map*, which is an excellent property in terms of neutrality. In this way a location does not receive benefit/penalization when compared to other points having different number of channels. The algorithm can be formalized the following way:

$$score_{i,p} = \sum_{c=1}^N |D_{i,c} - D_{p,c}| + (k-1) \cdot |SD_{i,c} - SD_{p,c}| \quad (\text{eq. 5.5})$$

Where D is the ICRD, SD is the SPD-ICRD, N is the number of channels, k is the SPD-ICRD weight, i is the on-line location index and p is the *radio-map* location index.

According to equation (eq. 5.5), the algorithm takes all differentials (ICRDs), including the Same-Propagation-Direction, and attributes them the same weight. In order to take advantage of the high correlation properties with same direction channels, this differential is given a higher

weight (k), but since it had been considered once in the summation part of the equation, the weight becomes (k-1).

Implementation

In order to implement the presented method as part of the Location framework, the previous expression was translated to software functions. In fact the algorithm was initially implemented in a direct way, following the conceptually required two steps: first, the calculation of the ICRDs; second, the comparison of the ICRDs between the *radio-map* and the fingerprint. Such implementation is very simple and can be represented by the following pseudo-code:

```
1. def point_calc_difs( channels_rssi ):
2.     # This is the implementation of the direct method
3.     """We expect a list in the format [[channel, val],...] """
4.
5.     dif_channels = []
6.     dif_values = []
7.
8.     for i,[ch1, val1] in enumerate(channels_rssi[:-1]):
9.         #Forward difs
10.        [ch2, val2] = channels_rssi[i+1] #Next
11.        dif_channels.append( [ch1, ch2] )
12.        dif_values.append( val1 - val2 )
13.
14.    #Dif between first and last
15.    ch1, val1 = channels_rssi[0]
16.    ch2, val2 = channels_rssi[-1]
17.    dif_channels.append( [ch1, ch2] )
18.    dif_values.append( val1 - val2 )
19.
20.    return dif_channels, dif_values
```

Nevertheless, such implementation lacks the flexibility required to cope with eventual incomplete or incompatible delta sets, e.g. when a fingerprint didn't capture all (sometime any of) the channels present in the *radio-map*, a very common situation even for samples taken in the same point. Therefore the equations were transformed to simplify the process and relax the requirement of having completely matching ICRD sets.

The transformation is based on the aggregation of terms from the same channel, as shown in (eq. 5.6).

$$\begin{aligned}
baseScore_{i,p} &= \sum_{c=1}^N |D_{i,c} - D_{p,c}| \\
&= \sum_{c=1}^N |(x_{i,c} - x_{i,c+1}) - (y_{p,c} - y_{p,c+1})| \\
&= \sum_{c=1}^N |(x_{i,c} - y_{p,c}) - (x_{i,c+1} - y_{p,c+1})| \\
&= \sum_{c=1}^N |\Delta_{i,p,c} - \Delta_{i,p,c+1}|
\end{aligned} \tag{eq. 5.6}$$

Where $\Delta_{i,p,c}$ is the RSSI difference between the online measurement at point i and the *radio-map* at point p for a channel c .

This transformation brings the equation a very important characteristic: the RSSI differences (Δ) are now calculated within the channel and the distance-norm is calculated in reference to the next channel Δ . Therefore, if a channel is not present either in the collected fingerprint or in the *radio-map*, the calculation can proceed and use the next common channel available.

5.2.3 HYBRID ALGORITHM AND DATA FUSION

Considering the ICRD metric as extra input for a localization algorithm, in addition to absolute RSSI, allowed for the development of a hybrid method. The hybrid method is implemented on top of the framework capability for processing the same dataset with different base algorithms and then merging them, given the weights values for each calculated point probability - see the details in the part “Interoperation protocols” from section 5.1.2.

Furthermore, having collected fingerprints from the GSM and WLAN networks, they were fed into the software both independently and combined. In this case the fusion was performed in a manner similar to that with multiple algorithms, having different data in one of the algorithms’ component, other than a different algorithm itself.

Implementation

Both Hybrid and Multi-Technology methods are based on the averaging of the individual components results. Since the results are in the form of scores converted to percentage, such scores can be combined by simply getting the average per point.

```

1. def match_hybrid(channel_values, icrd_weight=0.5,
2.                 abs_rssi_params, icrd_params, tech="gsm" ):
3.
4.     resu1 = match_diffs2 (channel_values, icrd_params, tech=tech)
5.     resu2 = match_abs_values(channel_values, abs_rssi_params, tech=tech)
6.     return combine_results( resu1, resu2, icrd_weight )
7.
8.
9. def match_multi_tec( channel_values1, channel_values2,
10.                    match_method, m1_params, m2_params, weight=0.5 ):
11.
12.     resu1 = match_method( channel_values1, **m1_params )
13.     resu2 = match_method( channel_values2, **m2_params )
14.     return combine_results( resu1, resu2, weight )
15.
16.
17. def combine_results( resu1, resu2, weight ):
18.     #Average existing from both
19.     glob_resu = []
20.     for resu1_val in resu1:
21.         for resu2_val in resu2:
22.             if resu1_val[0] == resu2_val[0] :
23.                 glob_resu.append( [resu1_val[0],
24.                                   resu1_val[1] + resu2_val[1],
25.                                   resu1_val[2]*weight + resu2_val[2]*(1-weight)] )
26.
27.     #Sort by new score
28.     return sorted( glob_resu, key=lambda x: x[2], reverse=True )

```

From the pseudo-code above, one can see that both `match_hybrid` and `match_multi_tec` rely on a common `combine_results` function, where the weighted average is performed (line 25).

Tests configuration

In order to having a test suite comprising all these scenarios, a total of six testing configurations were defined. Results are shown in corresponding section 5.3.3.

1. **Weighted KNN with GSM** - Use of the KNN's new weighting variant with GSM data.
2. **Hybrid (weighted & ICRD) KNN with GSM** - Both the algorithms are combined to perform as a single hybrid algorithm with GSM data.
3. **Weighted KNN with WLAN** - Use of the KNN's new weighting variant with WLAN data.
4. **Hybrid KNN with WLAN** - Both the algorithms are combined to perform as a single hybrid algorithm with WLAN data.
5. **Multi-technology Weighted KNN** - Use of the KNN's new weighting variant with GSM and WLAN data fusion.
6. **Multi-technology Hybrid KNN** - Hybrid algorithm with GSM and WLAN data fusion.

5.3 EXPERIMENTAL RESULTS

The initial experiments for localization considered the first collected *radio-map*, which had a resolution of 40 m, and a simple nearest-neighbor (NN) matching algorithm (Pereira, et al., 2011). The method yielded an accuracy of 80 m in 64% of the cases for the best guess. Since in a NN approach the error takes only values which are multiples of the calibration resolution, i.e. 40 m, this value is within the expected range but it can still be considered as very conservative. Besides developing the algorithms, the new experiments described here are a refined version which were conducted using *radio-maps* of 10 m resolution and testing a set of different algorithm parameters, including KNN's K value and the weight of each component in the hybrid approaches. The improvements, as shown throughout the section, are considerable.

5.3.1 WEIGHTED KNN ALGORITHM WITH GSM ABSOLUTE RSSI

In order to perform a comprehensive analysis, the radio maps and fingerprints were tested against each other in various configuration of the two sessions (*radio-map* and online fingerprints), the two mobiles phones, and whether mean or median was used to represent the distribution. Regarding the sessions, two approaches can be taken: (1) the fingerprints are considered alone or (2) merged across sessions. These four dimensions of parameters define 24 configurations (Note: *radio-map* Session2 was not considered since it wouldn't introduce a new scenario). The cumulative accuracy curves were calculated for each scenario.

As a first assessment of their accuracy, to avoid displaying all the plots, the average accuracy in the distance-error between 0-120 meters was calculated using the base NN algorithm. The results are shown in Table 8. The complete results, including the accuracy curves of each the 6 scenarios for the [Mean/Merged mobile] settings - values in bold - are found in Appendix C.

TABLE 8 - NN AVERAGE ACCURACY

Online fingerprints source		Session 1		Session 2		Sessions Merged	
Distribution representation → Mobiles used ↴		mean	median	mean	median	mean	median
Radio-map Session1	Independently	76.724	78.736	43.966	43.391	47.414	49.425
	Merged	89.368	91.092	49.425	48.563	60.632	59.483
Radio-maps merged	Independently	64.655	63.506	47.701	44.828	74.138	71.839
	Merged	68.966	69.540	60.632	58.333	87.644	87.644

Please note that accuracy at a certain distance error is given by the percentage of samples that the NN correctly identified within that range. E.g.: The accuracy at zero distance-error represents the percentage of samples whose position was exactly identified. The reason why the averaging was stopped at 120m is due to the fact that at 120m almost every method reached 100% and performance beyond this range is no longer relevant for the study.

From the table, important conclusions can be drawn. We start by noticing that it is mostly irrelevant whether the mean or the median is used to represent a fingerprint distribution, accounting for at most 4% of the difference, both improving and worsening. On the other hand, we notice a small but constant improvement when the mobiles are “merged”. That means that the samples are considered as if they were coming from the same source to build a single fingerprint, both for the *radio-map* and the online fingerprints.

Independent sessions

One can observe that the group [*Radio-map* session 1 / Online fingerprints session 1] - the first square - is, without doubts, the one performing the best. This doesn’t really come by surprise. Since the data taken for online and offline phases have origin in the same session, it is guaranteed that the conditions are identical. Therefore, even if the samples are independent, the fact that they are collected in the same exact position at nearly the same time will greatly improve their matching.

Nevertheless, in the current scenario, these conditions are considered ideal. As seen in the previous chapter (e.g. in Figure 20 and Figure 21), the fingerprint values considerably change among the sessions. Accordingly, the performance of the group [*Radio-map* session 1 / Online fingerprints session 2] - the second square - is greatly affected, ranking the lowest among the 6 groups. This fact strongly supports the conclusion that the RSSI variations found among different sessions will negatively impact the performance of localization algorithms.

Merged Sessions

An approach investigated, initially for matters of study completeness, is the merging of the sessions, considering the fingerprints as if they had been collected in the same single session. This approach was partially used in (Pereira, et al., 2012), in the sense that it used a merged *radio-map*, but both fingerprinting sessions were independently fed to the KNN. This approach yielded more stable performance metrics, i.e. they would vary less with the session - see groups 1 and 2 in the row [*Radio-maps Merged*] of Table 8.

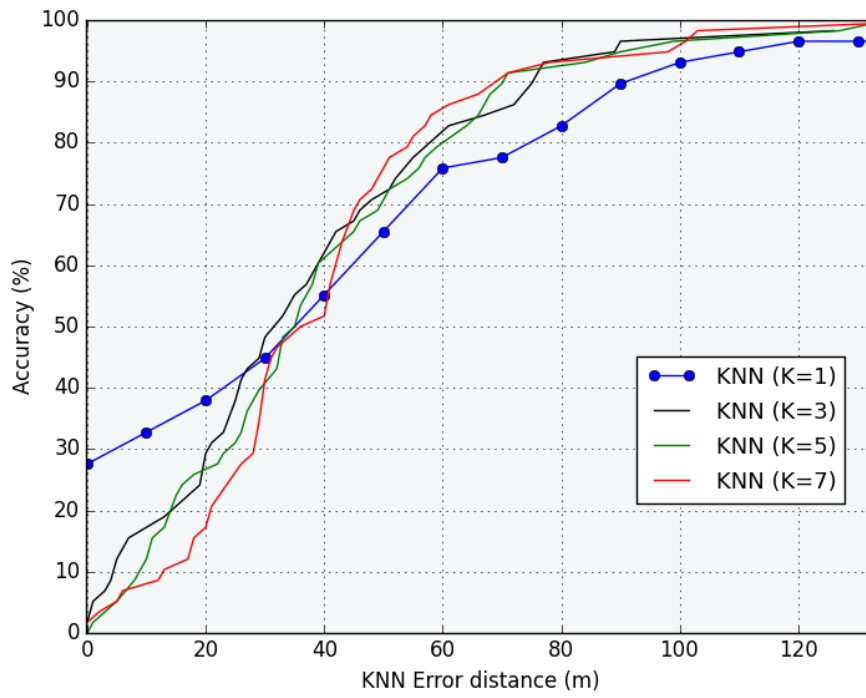


Figure 34 - KNN accuracy for GSM with merged *radio-map*.
Performance evaluated with KNN for K=1 (NN), 3, 5 and 7.

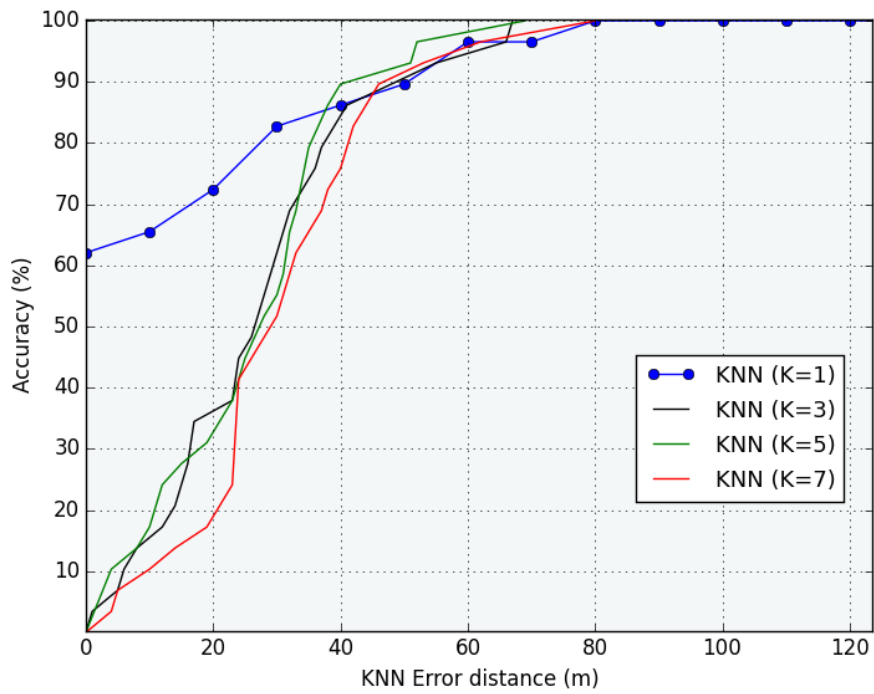


Figure 35 - KNN accuracy for GSM with merged *radio-map* and online fingerprints.
Performance evaluated with KNN for K=1 (NN), 3, 5 and 7.

The results are shown in Figure 34. In such conditions, which are very realistic and can be easily implemented, one can achieve accuracies better than 70 meters at 90% confidence, obtained using KNN with $K=5$ or $K=7$. Even though this is a significant improvement from the original results from (Pereira, et al., 2011), performance can still be regarded as conservative considering the best case seen before. Such lower performance stems from the fact that a merged *radio-map*, with sources that are different enough, might create a bimodal distribution for which the global mean is not generally very representative - see Figure 12 for an illustration.

Considering this, session merging was taken one step further, and applied to the online fingerprints as well, producing the third column [Sessions Merged] of Table 8. Looking to the values of the last group where the merged *radio-map* is also used, one can observe much better performance indicators, surprisingly close to the ideal case. With this method, even though mean or median properties are being used to represent the fingerprint, they can fairly compare an online fingerprint having a wide or bimodal distribution with a *radio-map* fingerprint of the same characteristics. The error-distance vs accuracy plot is presented in Figure 35. With merged *radio-maps*, an accuracy better than 40 meters is achieved in 90% of the cases by KNN ($K=5$). All other methods followed closely, requiring 50 meters for the same confidence level. These results improve the achieved accuracy levels obtained previously by a considerable margin: 32% in average.

From an implementation point of view, the latter method is more difficult, as it is impossible to know a-priori which other online fingerprint data to merge. A plausible way to find the additional fingerprints to merge would be to actually collect more fingerprints in slightly different conditions, as if they were carried out in different sessions.

Results with the New Weighting Method

The new weighting method, as described in section 5.2.1, takes into account an assessment of the quality of the RSSI sampling. According to benchmarks - Figure 33, the method would yield small improvements, but nevertheless a real-case test would be desirable to see how it performs in terms of Accuracy vs Error distance.

The absolute RSSI matching routine was modified to consider this factor and results calculated using a merged *radio-map*. The results are shown in Figure 36 and Figure 37, in terms of absolute performance and improvement from the base Weighted KNN (Figure 34) respectively.

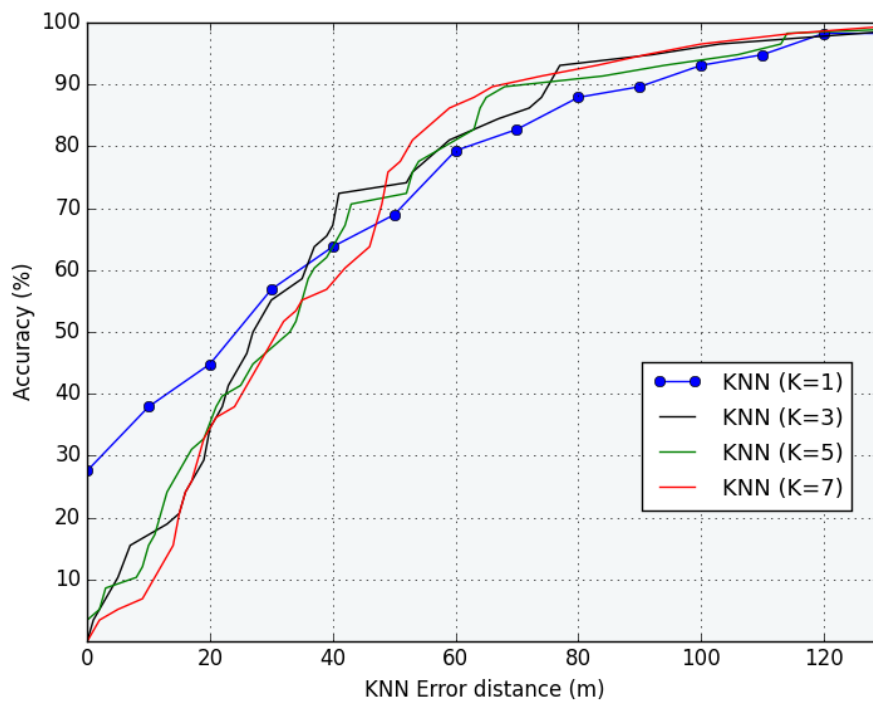


Figure 36 - New weighting method in KNN, with GSM network and merged *radio-map*. Performance evaluated with KNN for K=1 (NN), 3, 5 and 7.

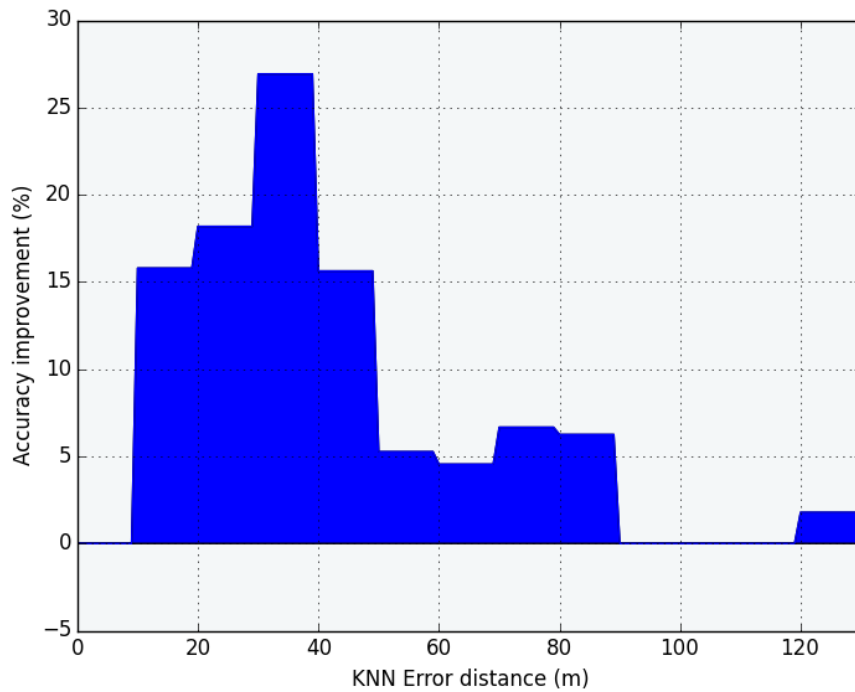


Figure 37 - Performance improvement with the New Weighting Method with KNN (K=1)

The results are quite interesting. From Figure 37 we clearly see an improvement of the performance throughout the whole error-distance domain, up to 27%. Indeed, in the region of 30 to 40 meters of error-distance, the algorithm yielded an accuracy of up to 57%, compared to 45% before. Besides, the better accuracy is achieved without penalty in other regions. The worse scenario is around the 0 region and between 90-120 meter error-distance where there isn't any improvement.

Given that the region of 40 to 80 meters is the one of most interest for this particular application, any improvement in accuracy is important and the fact that this method improves in that region "for free" is very positive. Nevertheless other alternative methods seeking for more accuracy were explored.

5.3.2 DIFFERENTIAL RSSI AND HYBRID ALGORITHMS

The differential RSSI - or ICRD-aware - methods introduced in 5.2.2, consider the power separation (or deltas) between the channels. They disregard the absolute RSSI value, and indeed that information is completely irrelevant and lost along the process. This novel approach was tested in exact same conditions as the absolute RSSI tests of the previous section.

The distance-error plots presenting the performance of the method with exact same conditions as the tests before, i.e.: merged *radio-map* and independent fingerprints, is shown in Figure 38. As can be seen, the accuracy of the method follows very closely that of the base absolute RSSI method. For better insight, the accuracy ratio between the methods was calculated and is presented in Figure 39. From the comparison it is clear that performance is improved in the region 20-90 meters up to 13.6%, but also penalized in the first guess (0-meter) and after 90 meters-error. Even though the 80 meter region is of interest for the specific application, an improvement of 4.2% is still moderate, especially if one accounts for some statistical fluctuation. Therefore, even though the method yields comparable - and sometimes better - performance than the base absolute RSSI method, its value resides in the fact that, by definition, the ICRD methods is more resilient to network power or device calibration changes, potentially reducing the need for *radio-map* recalibration.

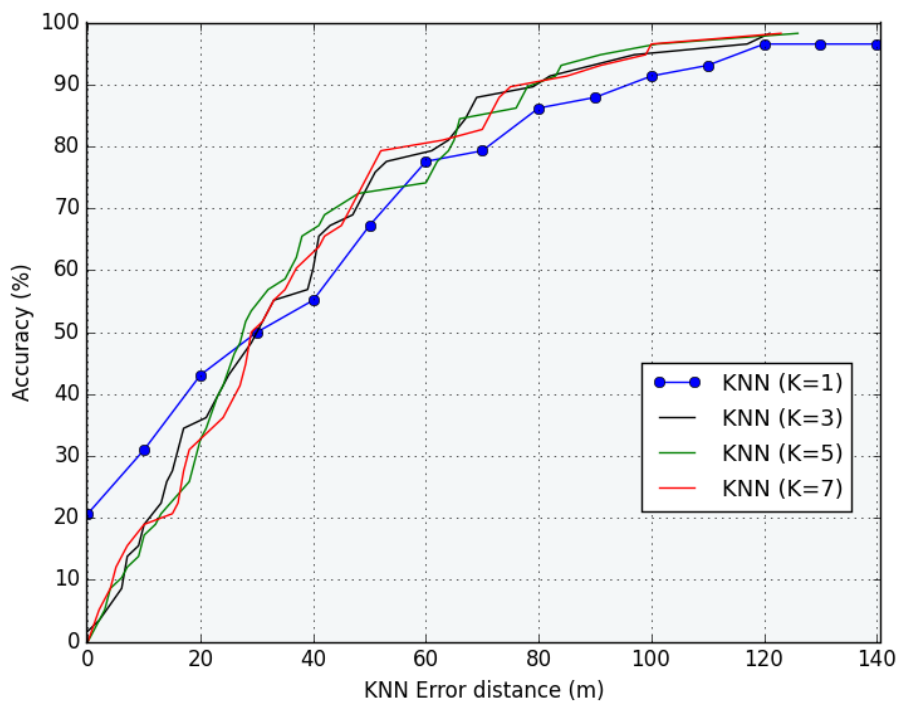


Figure 38 - Performance of the ICRD algorithm using merged *radio-map*

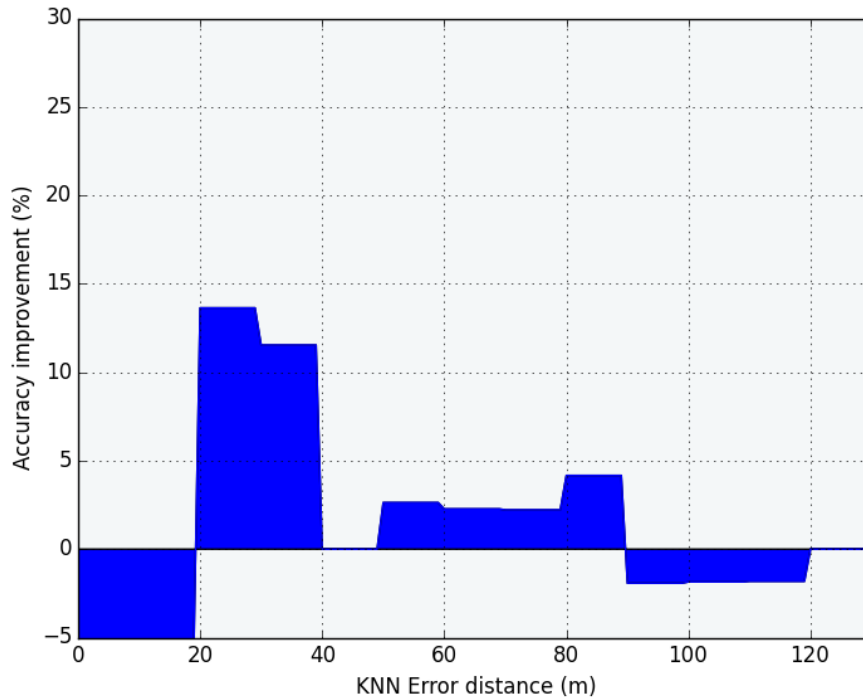


Figure 39 - Relative performance of ICRD algorithm compared to base RSSI method

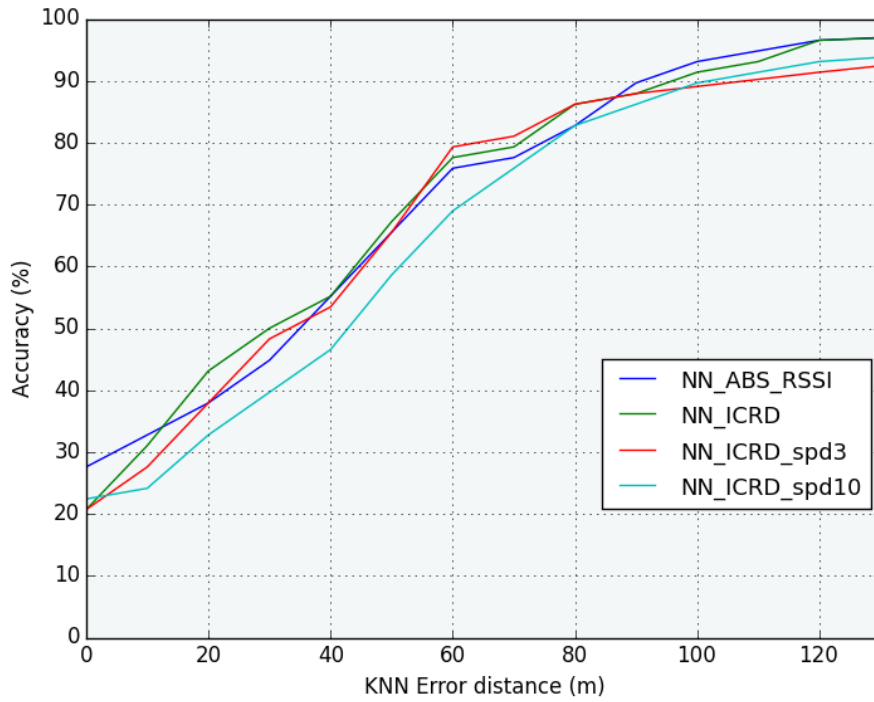


Figure 40 - Performance of ICRD method with different values of the SPD weight. Comparison performed with KNN (K=1) against the base Absolute RSSI method.

Same-propagation-direction (SPD) factor and Hybrid variants

The SPD factor works by giving extra weight to the differential between channels propagating in the same direction. Values of 3 and 10 were tested against the base absolute RSSI method and base ICRD and the results presented in Figure 40.

The tests suggest that no significant improvement can be found by defining such additional weight parameter. Instead, performance seem to be negatively affected when such channel is given a heavy weight (e.g. spd=10).

A Hybrid variant, which combines both Absolute RSSI and ICRD methods was also developed in the study, as introduced in 5.2.3. However, limited performance improvement was found with GSM. Therefore the performance of the method is presented in the next section, jointly with WLAN performance analysis.

5.3.3 PERFORMANCE WITH WLAN AND IMPACT OF DATA FUSION

WLAN experiments are relevant to the current study for two main reasons. First it provides an insight on the performance in case such technology becomes permanently adopted in tunnels used at CERN. Second, it allows us to understand whether the relatively moderate performance levels achieved with GSM are also due to the technical properties of the network, especially that RSSI are generally low and little changing due to the leaky feeder. The data collection setup is the same as presented in Section 4.3, featuring the two Access Points and shield foils.

As a first localization test (Pereira, et al., 2012), the average error of all the online fingerprints was calculated for all ABS_RSSI, ICRD and HYBRID algorithms with KNN K values of 1, 3, 5 and 7. The test was applied to both GSM and WLAN networks and accuracy results as plotted as a function of KNN values - see Figure 41. Second, the typical accuracy vs Error-distance plot is computed with the exact same parameters as for GSM, i.e.: merged *radio-map*, independent fingerprints - see Figure 42.

In Figure 41(a) it is noticeable that, with GSM, the performance of all methods gets better as more locations (K) are considered by KNN. This might be due to the fact that, with such little differences in absolute value, finding the exact match of a location is very difficult and averaging the best guesses weighted by their degree of confidence indeed becomes a favorable option.

With WLAN - Figure 41(b) and Figure 42 - one can clearly observe a significantly better overall performance. In particular the Absolute RSSI matching method performs better than the

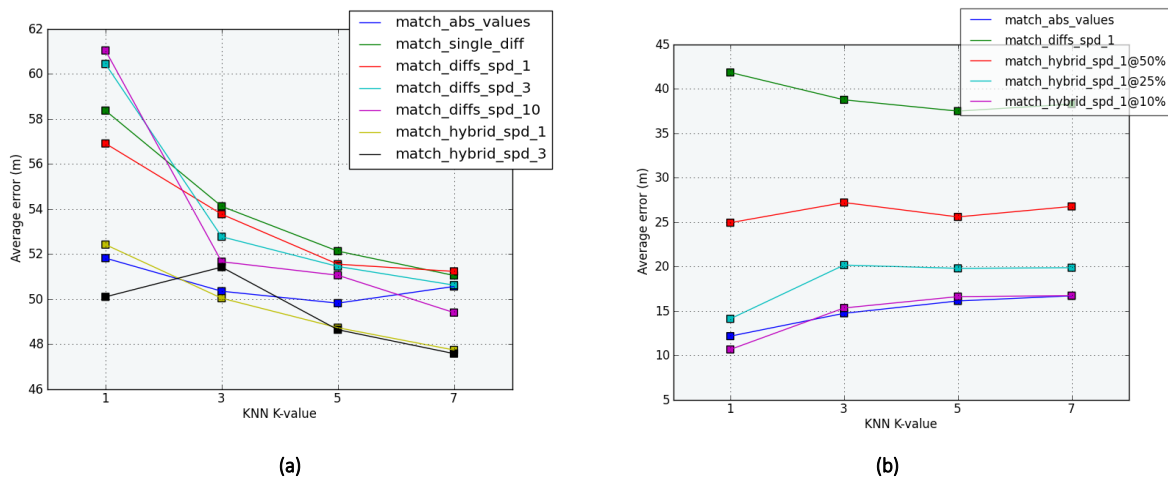


Figure 41 - Performance of the various KNN algorithms evaluated with GSM and WLAN

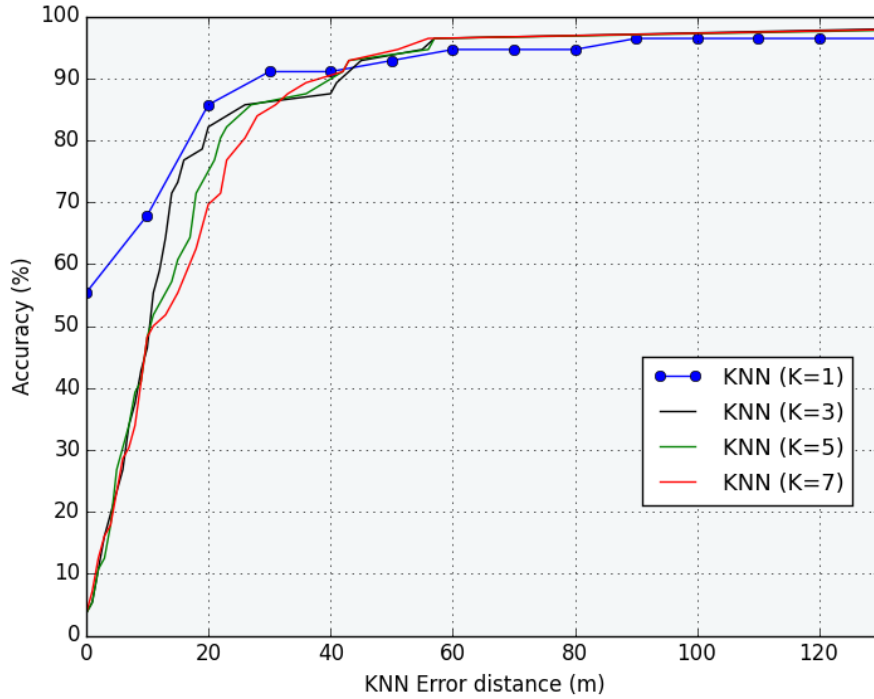


Figure 42 - Accuracy of KNN Absolute RSSI with WLAN network
Performance evaluated for K=1, 3, 5 and 7

ICRD and Hybrid algorithms - Figure 41(b). This behavior doesn't really come unexpected. The absence of multiple ICRD channels¹ in WLAN has a very negative impact, and therefore the average location error using the ICRD method is above 35m. Yet, this value is still better than the best method working over GSM. From Figure 42 one can clearly witness the better performance with WLAN, which provides an accuracy better than 30 meters in 91% of the cases, and 57m in 96.4%. In terms of average error (Figure 41(b)), the value sits at 12.1 m. This comparison clearly demonstrates that the performance of location fingerprinting methods is highly dependent on the underlying signal propagation characteristics.

It is also noticeable from both plots that with WLAN the best performance is, in general, obtained for the lower values of KNN K parameter. This result complies with the explanation that the higher the signal attenuation along the tunnel, the more accurate are the first guesses of the methods. In this case, for K=1 the absolute RSSI method yields an average distance error of 12.1 m.

¹ Recall that two RSSI channels create a single ICRD channel

Hybrid method results

The HYBRID method is obtained by combining both Absolute RSSI (ABS_RSSI) and ICRD methods - see Section 5.2.3 - whose component can be given different weights. Results of the Hybrid method compared to its base methods for both GSM and WLAN are shown in Figure 43.

With GSM one case see that the performance of Hybrid versus Abs_RSSI is somewhat improved in the 50 to 70 meters of error-distance but also somewhat penalized afterwards, and therefore its performance is rather inconclusive. With WLAN the results are interesting. The ICRD method, having a single channel, yields a poor performance and consequently a pure 50%/50% Hybrid method also has limited performance - Figure 43 line `match_hybrid_spd_1@50%`. However, when giving more weight to ABS_RSSI, the performance quickly improves to the extent that, in the regions of Error-distance > 40 meters or KNN with K=1, the Hybrid method yields a small yet permanent advantage. In such configuration, setting the distance error limit to 20 m, it provides an accuracy of 88.1%, which is quite interesting.

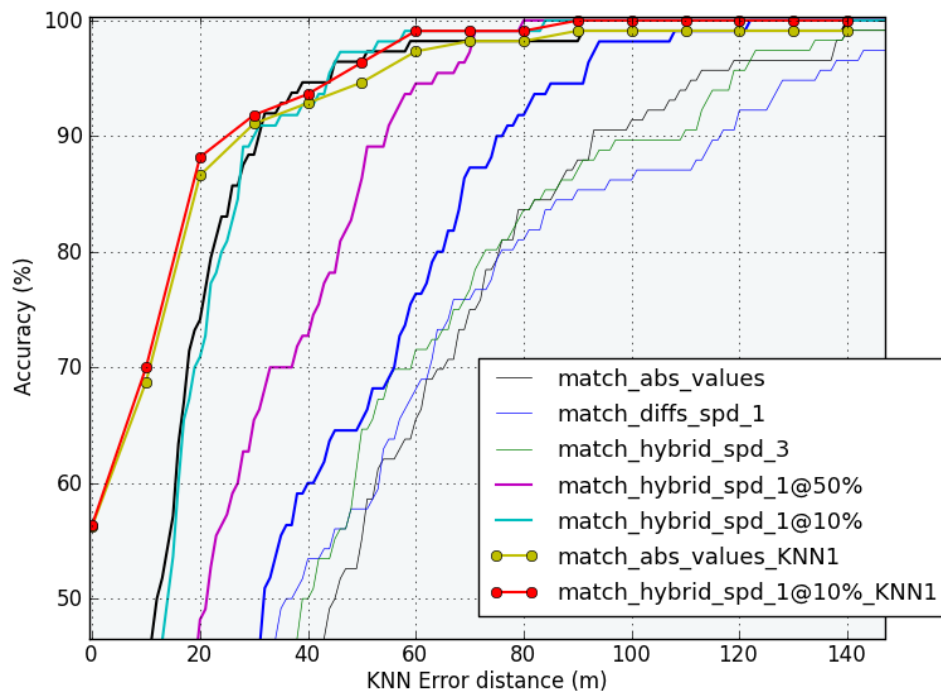


Figure 43 - Accuracy achieved by the HYBRID method with KNN (K=7, otherwise indicated). Thin lines are relative to GSM while bold lines are relative to WLAN.

Data Fusion and global comparison

The ultimate experiment regarding RSSI and KNN methods was to combine data from both networks and applying the developed methods. Data fusion was implemented by averaging results from either network, just as if they came from different methods altogether. Just like with the Hybrid approach, the averaging of results can be given a certain weight.

To assess the performance achieved in this case, a thorough comparison was made considering KNN (K=1) in the most significant configurations based on the previous algorithms. A resume of the methods settings is presented in Table 9 . For each method tested the technologies (networks being measured) are shown with their respective weights, always in parenthesis. For example, the description “gsm-hybrid-spd3+wlan-ybrid@10% (10%)” refers to the Multi-Technology approach using the hybrid method with both GSM and WLAN, where “@10%” means giving 10% weight to ICRD algorithm and the “(10%)” means that the GSM part is then weighted 10% (90% for WLAN)

The performance of the Absolute RSSI method for GSM (gsm_abs_values) and WLAN (wlan_abs_values) are included for base comparison, as both are then combined by the multi-technology method (gsm-abs+wlan-abs).

The results are shown in Figure 44 and provide an overall performance summary.

TABLE 9 - PARAMETERS OF THE COMPARED ALGORITHMS

NAME	TECHNOLOGY (WEIGHT)	MATCHING ALGORITHM	ICRD WEIGHT
gsm-abs_values	GSM (100%)	ABS_RSSI	0
gsm-hybrid-spd3	GSM (100%)	HYBRID (ABS_RSSI+ICRD)	50% (SPD=3)
wlan-abs_values	WLAN (100%)	ABS_RSSI	0
wlan-hybrid@10%	WLAN (100%)	HYBRID	10%
gsm-abs+wlan-abs (50%)	GSM (50%)	ABS_RSSI	N/A
	WLAN (50%)	ABS_RSSI	N/A
gsm-abs+wlan-abs (10%)	GSM (10%)	ABS_RSSI	N/A
	WLAN (90%)	ABS_RSSI	N/A
gsm-hybrid-spd3+ wlan-ybrid@10% (10%)	GSM (10%)	HYBRID	50% (SPD=3)
	WLAN (90%)	HYBRID	10%

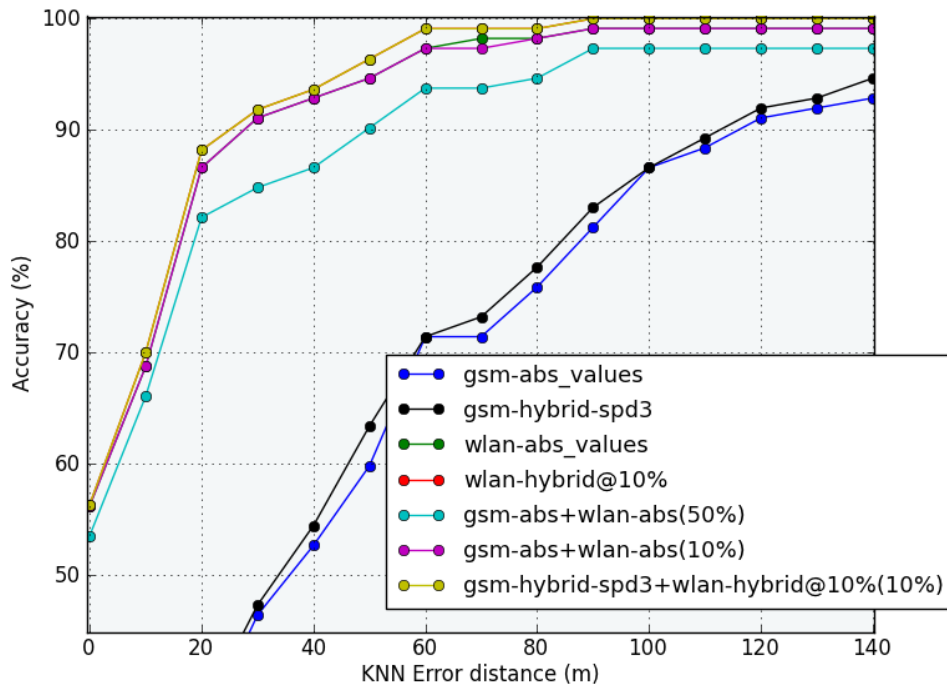


Figure 44 - Accuracy comparison among the various methods
Absolute RSSI, Hybrid and Multi-Technology evaluated with KNN (K=1).
Please note that red and yellow lines are totally coincident,
while green and purple lines also coincide except for one point.

The results show again, now with KNN, K=1 in all cases, the significant performance improvement obtained when the algorithms work over WLAN. Even when combining both technologies giving 50%/50% weights, the performance of this multi-technology method largely exceeds that from GSM alone, and approaches the one from WLAN. However, only when giving 10% weight to GSM – method gsm-abs+wlan-abs(10%) – the global performance improves and achieves the same level as WLAN itself.

When combining hybrid methods from the different technologies (gsm-hybrid-spd3+wlan-hybrid@10%), a similar behavior is observed. The algorithm yields an accuracy level identical to that achieved by the best underlying algorithm – wlan-hybrid@10% in this case. The fact that the multi-technology method doesn't improve on that result might be due to the highly uneven levels of accuracy achieved by the underlying technologies. Furthermore, in order to improve the already rather accurate guess with WLAN, one would need quite high confidence levels in the GSM matching (uncommon in the current data set) and eventually a location algorithm, other than KNN, that could take better advantage of the combined result set.

5.4 ASSESSMENT ON KNN'S PERFORMANCE LIMITS

In the previous sections the performance of fingerprinting methods was assessed for localization purposes in the LHC tunnel. Nevertheless the achieved accuracy values in this specific environment might seem low when compared to that achieved in other fingerprinting localization experiments which, as described in literature, can achieve accuracies better than 10 m at 90% confidence (Mautz, 2012).

5.4.1 ACCURACY UPPER LIMIT OF KNN

The methods investigated in the course of the studies were based on KNN working with the RSSI of the signal. Several more elaborated variants of the base Absolute RSSI matching were also investigated, including take advantage of the known power distribution to weight the difference between the samples and the fingerprints. It was shown that this information could be useful in situations where the *radio-map* contains fingerprints with a relatively large variance in the power distribution. Nevertheless the improvements vary between 0 and 25%, having its peak contribution in a region where method accuracy is relatively small (55% at error-distance of 40m). In the region of certainty better than 90% no improvement was found.

To assess possible accuracy improvements with KNN, an ideal KNN was designed with the current weighting methods and its accuracy computed for $K=2$ and $K=3$. The principles of the ideal KNN are the following:

1. It expects the list of positions and respective probabilities created by the matching method.
2. It returns the actual measurement position if it corresponds to any of the K elected fingerprints, i.e., the K fingerprints with higher probability.
3. Otherwise performs the default KNN averaging.

An inconsistent norm or weighting - see section 2.5.1 - could eventually contribute to limited accuracy of the ideal method as well, but in current tests only the Euclidian norm and no weighting are considered. The possible source of error limiting the accuracy is therefore only the disagreement between the values of the *radio-map* and the online fingerprints.

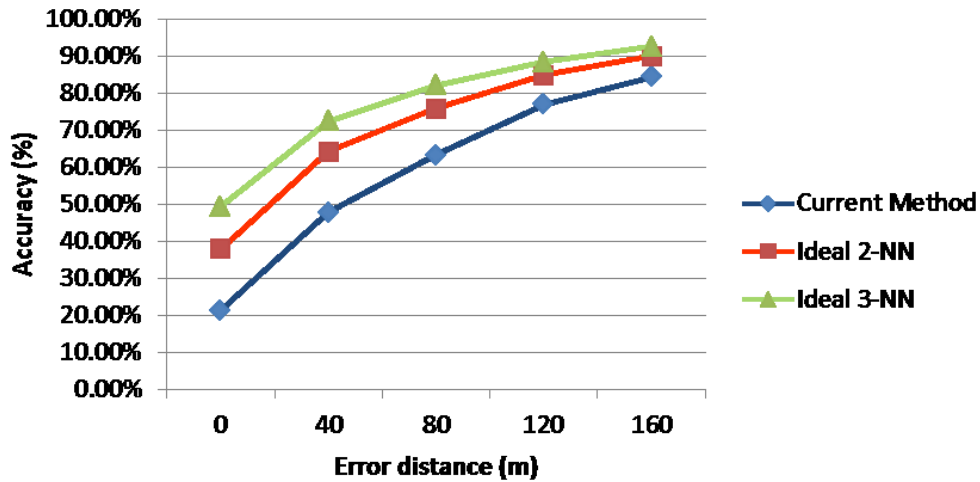


Figure 45 - Performance of the ideal KNN, for K=2 and K=3, compared to NN.
Initial GSM studies with a 40 m resolution radio-map

The ideal KNN was initially tested with the first network data collection (Pereira, et al., 2011), where the calibration was performed every 40 meters. The results are shown in Figure 45, and express a considerable improvement of the accuracy. It was found that the ideal KNN taking advantage of the three best-matched fingerprints (3-NN) could increase the accuracy by 27% in the best case. It should also be noted that the advantage of the 3-NN over the 2-NN approach is at best about 10%.

Although the results with the ideal KNN method are very interesting, they looked poor in the global scene, as to achieve an accuracy of 80% the error distance is up to 80m. Nevertheless, we must take into consideration the conditions in which the tests and more specifically, the calibration were performed. In fact, given that the resolution of the current radio map is 40 m, 80 m correspond to the distance between three subsequent calibration points. If hypothetically our environment could offer the same signal characteristics for a *radio-map* taken with a resolution of 1 m, the achieved accuracy would then be in the order of 2 m for this ideal method and 3 m for our method, for a confidence of 80%.

Such rationale was one argument towards the higher resolution calibration phase - 10 meters - as presented throughout this thesis.

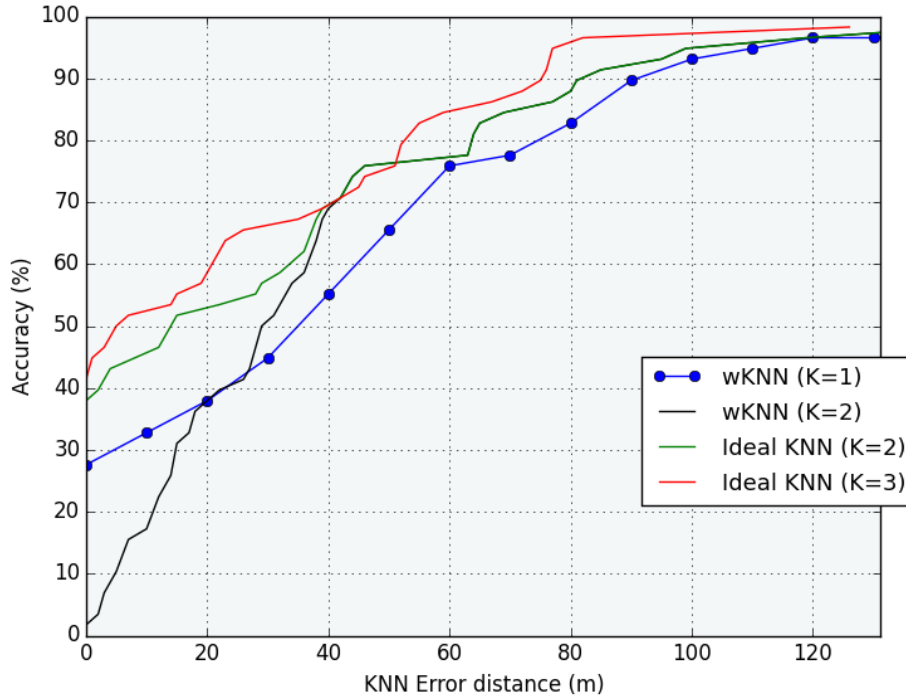


Figure 46 - Performance of the ideal KNN, for K=2 and K=3
Studies with GSM and a 10 m resolution radio-map

Impact of higher calibration resolution

To investigate on the impact of the calibration resolution, the ideal KNN was computed also against the new dataset, with a *radio-map* and fingerprints built with samples taken every 10 m. The results are shown in Figure 46.

Several important and interesting aspects can be extracted from the results. The ideal KNN performs, as expected, better than the normal KNN. We can see a considerable improvement of the ideal KNN, K=2 over the default wKNN K=2 until error-distance of 40 meters, and an overall improvement of the ideal version when it considers 3 nearest neighbors (ideal 3-NN) instead of 2, yielding up to 12% more accuracy.

However, the current *radio-map* already enables the base KNN to perform relatively well and, visibly, the ideal KNN improvement is considerably smaller compared to that in Figure 45. In fact, when both methods run with K=2, after error-distance 40 m, the performance of the ideal version is totally coincident with that of the default weighted KNN. Another peculiar event happens in the region 40-50 meter error-distance, where the performance of the ideal 2-NN

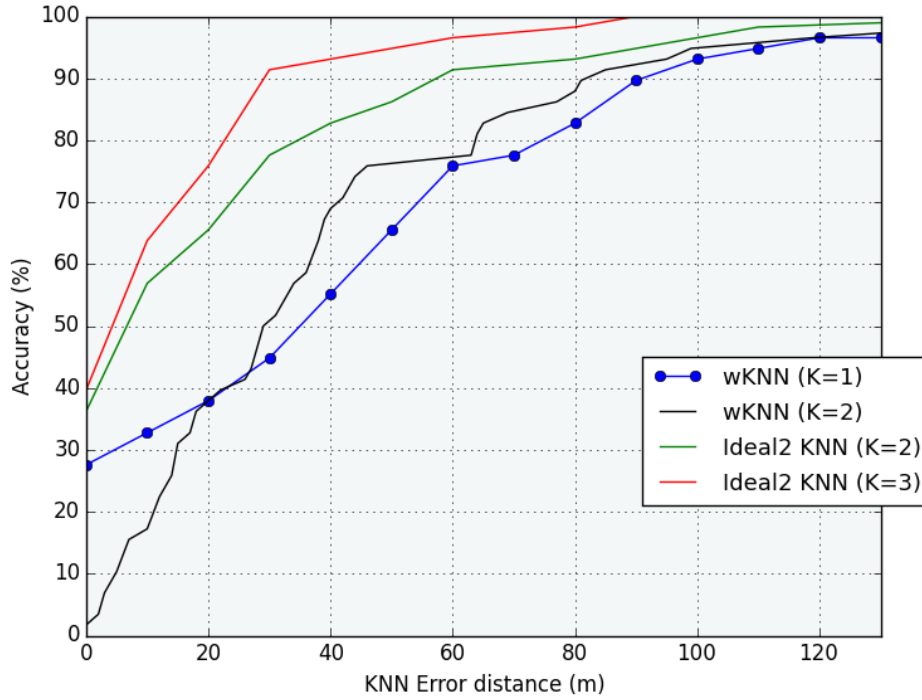


Figure 47 - Improved Ideal KNN, which doesn't fall back to default KNN average
Studies with GSM and a 10 m resolution radio-map

exceeds that of the ideal 3-NN. Both events are connected and were traced back to the same origin: the case when the actual position is not among the K elected positions in the list and the default KNN averaging is applied - see point 3 of the ideal KNN definition. With $K=2$ that happens very frequently and explains the superposition of the lines. With $K=3$ that happens much less often, but makes it possible that the additional position to be considered by the 3-NN makes the averaging further away from the real value, given that none was the correct. In order to give further evidence on that, a new ideal KNN was computed where, instead of computing normal KNN when the real position is not in the list, it will return the best position from that list. The result plot is shown Figure 47, and one can observe a very significant improvement of the accuracy in the whole domain, with an exceptional peak at 30 m error-distance: 77% ($K=2$) and 91.4% ($K=3$) where the default KNN performs at 50%.

Such result confirms that, contrary to what may be intuitive, it is very common that the true position is not among the best matches. Nevertheless, as seen in Figure 47, it is very common that this list contains a close position (up to 30 m distance), which explains why such a situation doesn't occur so often when the *radio-map* has a coarser resolution. On the other hand, it also

happens frequently that the K-elected positions are relatively far from the real point, and therefore the default KNN averaging is largely surpassed by a truly ideal situation that only the closest point is selected and the others discarded.

5.4.2 OTHER FACTORS LIMITING ACCURACY

Even though conditions for reliable signal stability can certainly be found in many static environments, the tests carried out in the underground suggest that under normal working conditions in an underground tunnel, where other pieces of bulky and massive equipment and personnel are present, such conditions are hardly possible to achieve. That implies that the differences between measurement sessions are significant and therefore that the matching algorithms often don't correctly find the nearest position, or include positions which are relatively far away.

It should also be noted that in addition to the specific and unique nature of the accelerator equipment in the tunnel also their operation conditions might change at times, like the power conditions of magnets. Even though no specific studies on the influence of these parameters have been done yet, it cannot be fully excluded that there might be an impact.

Regarding the *radio-map* resolution, there was a notable improvement from 40 m to 10 m calibration distance. Further tests have been performed to assess the performance for a calibration with a resolution in the order of 1 meter. It was found that the spatial and in-time fluctuations of the network electromagnetic fields overwhelms the signal small attenuation caused by propagation along a leaky feeder. Eventually other networks, where the RSSI is expected to vary in a shorter scale, might benefit from such high-resolution *radio-maps*.

5.5 CONCLUSIONS

This chapter presented the experiments regarding localization performed using GSM and WLAN signals in the LHC tunnel. It presents several KNN variants which, working over real RSSI fingerprints, computed positions and their accuracy was evaluated in terms of error-distance and accuracy percentage (or confidence).

The base-comparison method is a direct implementation of the weighted KNN, amply mentioned in related literature. Given that two data sessions are available, several approaches of data merging are studied. The approach in which merging happens in both the *radio-map* and the fingerprints are highly effective, reaching with GSM accuracies better than 50 m in 90% of the cases. Nevertheless, given the difficult practicality of the approach, the base approach selected for the next experiments is that of the merged *radio-map* only. With the plain weighted KNN method it yields accuracies limited to 70 m error in 90% of the cases.

Among the new explored approaches are a KNN method with a new weighting factor, which takes into account the fingerprints distribution, the ICRD method, which takes advantage of the channels RSSI differential, and a hybrid approach. When considering GSM, the first approach shows to improve accuracy in the region up to 90 m error by a factor of up to 27% higher, without harming accuracy in any accuracy zone. The ICRD method showed a performance compatible with that of the base method, but its strength relies on the potential reduction of the need for recalibration. The Hybrid approach was found to achieve as well comparable results as the base method.

Tests with WLAN were performed in similar conditions and allow for much better accuracies. One can reach 30 m of maximum distance-error in 91 % of the cases with base weighted KNN, and a small improvement (1 to 2% more) when using the hybrid method. A Multi-Technology approach was tested as well, where computations from both networks were taken into account. Nevertheless the GSM contribution could not help the Hybrid method to improve the interesting accuracy levels obtained by WLAN itself, achieving only coincident performance.

As last, an ideal KNN was modeled to provide a better understanding on the accuracy upper limits of RSSI fingerprinting approaches with KNN applied to the current data. It was found that with a 40 m resolution GSM *radio-map* the improvement is reasonably constant along all the error-distance domain, increasing the accuracy by up to 27% more, while in 10 m resolution *radio-map* the possible improvement is moderate. This is due to the higher probability of the K-best

matches to not include the correct position of the measurement. In those cases, if instead of defaulting to the KNN averaging one selects the closest location, accuracy is considerably increased again, up to 30m error-distance at 91% confidence.

Such test provides a good hint that the underlying matching methods are actually quite effective in selecting good matches. However, it is virtually impossible to achieve a KNN implementations reaching those performance limits, since the information required to select the best locations doesn't exist in a real situation, and in the ideal case they were artificially fed into the calculation. Unless other measured information, other than the RSSI, are fed to the KNN or time-evolution techniques (e.g. filters) are applied, to better rank the possible positions, the performance with KNN seems quite limited to those accuracy figures achieved before, in the same range found with the weighted KNN approaches.

ENHANCING LOCALIZATION ACCURACY WITH NARROWBAND TECHNIQUES

This chapter presents the design of a complementary localization system capable of achieving higher accuracy levels, and its validation via a prototype implemented using SDR, in contrast to dedicated hardware. The following sections introduce the principles behind phase-delay positioning and SDRs, the conducted experiments, the developed methods, their implementation and, finally, their performance. In the end an overview of a joint localization system using both RSSI fingerprinting and phase-delay is presented.

6.1 INTRODUCTION

For the purpose of localization in the CERN accelerator tunnels, techniques based on RSSI fingerprinting have been previously explored, which took advantage of the dense network coverage available via a set of leaky-feeder cables. Even though RSSI-based methods have shown to be effective in estimating the location their best accuracy was achieved with WLAN and was limited to 20m at a confidence level of 88%. With GSM the accuracy was limited to 70m at 90% confidence in realistic conditions, which is not sufficient for providing an accurate position tag for some applications.

6.1.1 MOTIVATION AND OBJECTIVES

Besides the benefit with respect to increased personal safety, a good level of accuracy, in the order of one to two meters, would enable for much faster processes carried out by various technical departments at CERN, including radiation surveys with automatic position tagging. In order to increase the accuracy up to the envisaged levels, techniques based on Time-of-Flight (RF wave propagation delay), that could meet the tunnels restrictions and specificities, have been

investigated. By measuring the carrier phase-delay in the VHF band (2m wavelength), the technology aims at achieving 1 meter-level accuracy and, by propagating the signal over the leaky-feeder cable, full tunnel coverage is expected to be achieved with a small number of units. With the purpose of validating the approach and, at the same time, prove that alternatives to the traditional integrated-circuit approach exist, the algorithms were prototyped using programmable Software Defined Radio (SDR) devices.

6.1.2 OPPORTUNITY FOR ToF USING PHASE-DELAY

Technologies based in Time-of-Flight - see section 2.3.1 - are arguably those enabling for the highest accuracy levels, typically reaching resolutions better than 30 cm in a 3D coordinate system. Nevertheless, due to the very high propagation speed and multi-path effects, these techniques generally require synchronization between the elements - e.g. GPS - or to send very short pulses whose delay is measured. The latter technique is known as ultra-wideband (UWB) due to its large spectrum consumption. In both cases the implementation is quite naturally done in hardware due to the strict requirements in terms of signal processing. Due to the several reasons presented before, including the impossibility of developing and installing hardware in the tunnel, such approach is not viable to the current project.

The only option available is therefore to work in narrowband. If one considers delay measurement of the signal itself, without messages or pulses, it is actually conceivable obtaining a time-delay from the measurement of the phase of a carrier signal, which would theoretically not occupy any spectrum. Tests with audible frequencies were explored in (Viegas, 2005). Due to that, the processing requirements of the devices are much less strict and open the possibility of implementing them in software, tuned to the current scenario. On the other hand, having a signal that virtually doesn't occupy any band greatly reduces the risk of interference with existing hardware installed in the tunnel. Such property enabled the studies to comply with the hard restrictions imposed by the tunnel policies in-place, and therefore to proceed and being tested.

At the same time of the development of the current PhD work, a network being previously used for safety purposes entered its decommissioning phase. This network used frequencies in the VHF band and was, along with GSM, transmitted throughout the tunnel via the leaky-feeder cable system. Given that frequencies in the VHF band seem to be in the same range as those required for the localization signal, the decommissioning of the previous network seems

an excellent opportunity to the current work, which can benefit from existing VHF infrastructure and the guarantee that there's no interference in that spectrum region.

6.1.3 ADVANTAGES OF SDR

The SDR approach stands as a very interesting approach mostly due to its prototype friendly characteristics:

1. Fast development: The development time might get greatly reduced due to the availability of signal processing software libraries.
2. Fast development-to-test iterations: With SDR, there is no need of reprogramming or sending the device to be assembled. The SDR platform runs the code directly.
3. Relatively low development costs: For the same reasons as (2), costs are only associated with SDR devices, and will not increase with the number of development iterations.

Given that phase-delay techniques require little band and relatively little computation, SDR seems an excellent approach as long as the devices are capable of sampling rates obeying Nyquist criteria for the designed signal.

6.2 PHASE-DELAY POSITIONING AND SDR

Phase-delay methods are an alternative to UWB positioning and the techniques for obtaining the measure are quite different. UWB frequently employs pseudo-random noise (PRN) codes so that auto-correlation techniques can be applied at the receiver. Among the best known cases is GPS C/A (GPS.gov, 2014; Ávila Rodríguez, 2011) which employs Gold Codes of 1023 chips at 1 Mchip/s whose receivers are currently able to detect shifts in the order of 1% of chip time. That is $1\% \times 1 \mu\text{s} = 10 \text{ ns}$ which, at the speed of light, represents a spatial accuracy of around 3 m.

6.2.1 PHASE-DELAY TECHNIQUES

In systems using narrower frequency bands, even though multiple propagation paths can be more difficult to distinguish, the carrier phase can be recovered at the receiver. In these cases the accuracy is proportional to the wavelength, typically up to 1%, and therefore cm-level accuracy can be reached as well.

Phase delay techniques work fundamentally with pure sinusoidal waves from which the phase is to be recovered. Nevertheless, some bandwidth is normally required. Firstly for target disambiguation (or identification) in case the location is computed by a central unit. Secondly, and depending on the design, some elements of the system may have to be synchronized, typically between the sender and the receiver or among several emitters. This requirement introduces an additional need for transmitting either synchronization messages or several reference sinusoidal waves, which in both cases can be considered as band. Besides identification and synchronization, a third aspect is often desirable: extended range. Considering 5% accuracy in phase detection, 10 cm of spatial accuracy requires 2 m wavelength signals. Without disambiguation, two meters would therefore be the localization range, which might be too short for many applications. These aspects are briefly introduced and define the foundations of the developed technique.

Phase detection and drift correction

In perfect conditions, the phase can be directly detected by very simple circuits which are indeed called *phase detectors* or *phase comparators*. They are an essential element of Phase-locked-Loops (PLLs), widely used to generate waves themselves. PLLs are simple and nowadays implemented as highly integrated circuits, and so became an economical mass-production answer to the electronics industry needs, notably supporting the wireless revolution (Barrett, 1999). Despite impressive evolution over the years, PLLs are not ideal and their quality can be assessed, among other, by their frequency accuracy and jitter (phase noise). Such limitation is associated with the crystal oscillator used which, for commodity Temperature Compensated Crystal Oscillators (TCXOs), is commonly found to be around ± 2.5 ppm over -30°C to $+75^{\circ}\text{C}$. (Cerdea, 2005). Even though 2.5 ppm might sound extraordinary, it translates to a frequency shift of up to 100 Hz on a 25 MHz wave, which is enormous for phase sensitive applications.

To compensate for the mentioned limitations, two alternatives exist: employing a drift correction signal or using the same clock (and device) for both wave generation and phase detection which implies a round-trip architecture. Both methods were explored in this thesis. Round-trip methods are conceptually simpler, but are nevertheless technically challenging due to requirement of no phase distortion along the path even though different frequencies must be used for each direction. The implementation details of the latter are given in section 6.4.2.

The **drift-correction** method requires an additional reference unit that generates a corrective wave that compensates for the frequency and phase shift. The principle is as follows. Let us consider a sinusoidal of frequency f_c emitted by the element we want to measure position. The phase, in cycles, of the signal at a specific time can be expressed as:

$$\varphi(t) = \varphi_0 + f_c(t - t_0) \quad (\text{eq. 6.1})$$

Where φ_0 is the initial phase and the second term expresses the variation induced by frequency. If one takes the position of the sender and the receiver into account it becomes:

$$\varphi(x, t) = \varphi_0 + f_c(t - t_0) - \frac{d_{x_0}(x)}{\lambda_0} \quad (\text{eq. 6.2})$$

Where d is the distance between a position x_0 (fixed) and x , which is exactly the term sought to find out. It would therefore be desirable to have an expression not dependent neither on the frequency variation nor on the initial phase, i.e.:

$$d_{x_0}(x) = F(\varphi_{\lambda_0}) \quad (\text{eq. 6.3})$$

A theoretically simple approach to remove the terms that do not translate to position is calibration. If there would be a trustful reference of the exact emission frequency, the phase at position zero the receiver could, independently of its own clock, remove the unwanted terms.

The problem stems from the fact that it is impossible to directly generate a wave having the exact same frequency as the emitter without being coupled with it and without introducing the distance term. For that term to be null, as a base design, the receiver and the calibration device positions must actually be fixed in relation to each other. In the case of a calibration device which would adapt to the emitters, one can even consider a design where the calibration device is bound to the receiver and the number of infrastructure units are kept to the minimum. In the proposed solution this is the selected design - a single emitter.

Given that it is impossible to recover the emitter's exact frequency, the solution is to work around it and use phase differentials. Let us consider that the emitter transmits a second wave with a slightly different frequency close to f_c , $f_c + f_\Delta$ and that the unknown frequency errors to be eliminated are represented by f_e , the waves' equations are given by (eq. 6.4).

$$\begin{cases} \varphi_1(t) = \varphi_0 + [f_c + f_e](t - t_0) - \frac{d_{x_0}(x)}{\lambda_0} \\ \varphi_2(t) = \varphi'_0 + [f_c + f_\Delta + f_e](t - t_0) - \frac{d_{x_0}(x)}{\lambda_0} \end{cases} \quad (\text{eq. 6.4})$$

Where f_e , at the receiver side, is not only the frequency shift caused by the clock drift at the emitter, but also due to the clock drift at the receiver itself.

Based on these two signals, the reference unit can now create a third one (φ_3) whose phase difference to φ_2 is the same as between φ_1 and φ_2 , i.e.:

$$\varphi_3(t) - \varphi_2(t) = \varphi_2(t) - \varphi_1(t) \quad (\text{eq. 6.5})$$

From the receiver's perspective, the waves are

$$\begin{cases} \varphi_1(t) = \varphi_0 + [f_c + f_e](t - t_0) - \frac{d_{x_0}(x)}{\lambda_0} \\ \varphi_2(t) = \varphi'_0 + [f_c + f_\Delta + f_e](t - t_0) - \frac{d_{x_0}(x)}{\lambda_0} \\ \varphi_3(t) = \varphi''_0 + [(f_c + 2 f_\Delta) + f_e](t - t_0) + \varphi_K \end{cases} \quad (\text{eq. 6.6})$$

The advantage with φ_3 is that it no longer depends on the distance $d_{x_0}(x)$, but rather on a constant phase shift φ_K which depends only on the transmission delay between the reference unit and the receiver.

Taking the phase difference at the receiver between waves 2 and 3, one ends up with:

$$\Delta\varphi = \varphi''_0 + f_\Delta(t - t_0) + \varphi_K - \frac{d_{x_0}(x)}{\lambda_0} \quad (\text{eq. 6.7})$$

Considering that φ''_0 and φ_K are constants that must be calibrated at startup, the only requirement is to remove the $f_\Delta(t - t_0)$ term. By carefully choosing f_Δ to be small enough, the clock offset of a demodulator signal having frequency f_Δ becomes negligible and the phase dependent on $d_{x_0}(x)$ only can be recovered.

Cycle disambiguation for extended range

In phase-delay methods the localization range is the signal's wavelength. In order to overcome such limitation, disambiguation between the different cycles (or epochs) must be performed. Such disambiguation can, conceivably, be performed as a second step of the exact same technique proposed before but using a longer wavelength. Such wavelength should therefore meet the following requirements:

- Allow for localization resolutions better than the fine-localization epoch.
- Be long enough to cover an interesting range. In the case of the LHC tunnel, it would be of most interest to cover a length longer than the resolution of the GSM RSSI methods seen before, i.e. > 100 m or < 2 MHz (propagation in copper).

However, the emission of a wave directly in that frequency poses several difficulties. In the first place, since it is in a different frequency band, one doesn't have the guarantee that it won't interfere with existing equipment and therefore might face authorization issues. Secondly, in order to avoid parallel demodulation paths or separate circuits, which would be impractical with SDR, it is of most interest to generate and process waves that are close together to allow performing a single conversion step between baseband and carrier.

The solution to the aforementioned problem is therefore to transmit a pair of waves whose frequencies, say f_1 and f_2 , are close but separated by the intended resulting frequency. As a result, by demodulating one wave with the other in the receiver one would obtain the expected wave. Taking advantage of the fact that one wave is already transmitted for fine-grain accuracy, only one additional wave must be transmitted for the coarse-grain localization to be possible. Since the additional wave must also implement a phase correction method, a set of three additional frequencies, separated by f_Δ , are required. Therefore, by having both techniques simultaneously, a total of six waves are required around a carrier, as exemplified by Figure 48. For reference of the actual frequencies being used, refer to implementation section in 6.4.1.

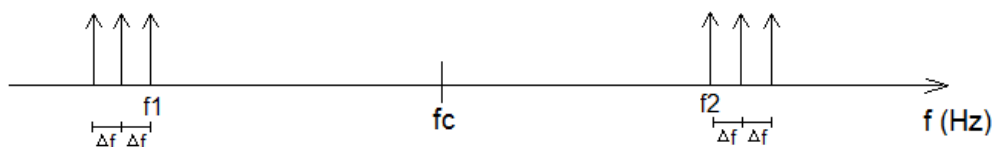


Figure 48 - Frequency plan using phase reference and epoch disambiguation techniques

6.2.2 SOFTWARE DEFINED RADIO PLATFORMS

Radio systems have traditionally consisted of transceiver chains with several stages, where the signal is converted to an intermediate frequency, filtered, then converted down to baseband and finally demodulated. With the advent of fast and inexpensive digital signal processors (DSPs), radio systems can now employ digital transceivers composed of a radio Front-End followed by an analogue to digital converter (ADC) and finally by a Back-End responsible for the further signal processing, like filtering and demodulation (Isomäki & Avessta, 2004).

The need for fast-paced development and prototyping has motivated the research for ways on how to change the behavior of some digital blocks with minimum time and cost, i.e. turn them software programmable (Mitola, 1995; SDR Forum, 1999). This class of transceivers is known as Software-Defined Radios and uses either Field-Programmable Gate Arrays (FPGA) or even General Purpose Processors (GPP) to perform digital operations equivalent to a traditional analogue transceiver (Isomäki & Avessta, 2004; Valerio, 2008).

Despite the increased degree of flexibility achieved in such configuration, FPGAs and more critically GPPs are intrinsically slower than Application Specific Integrated Circuits (ASIC). Therefore the computational requirements of the application must be carefully assessed to be sure they can be implemented in SDR. In the case of using GPPs, an intermediate FPGA is commonly used to perform the most demanding operations and down sample the signal to lower rates before sending them to the GPP. This configuration is the one evaluated in the current study.

SDR Architectures

The heterodyne receiver, as described in beginning of the current section, has been the most common RF front-end architecture. However, as SDR pushes the “digital” closer to the antenna, new architectures have been conceived towards minimal analog front-ends, notably the Direct Conversion and the Tuned RF receivers (Isomäki & Avessta, 2004).

Direct Conversion Receiver

The Direct Conversion Receiver (DCR) requires much less components and, due to its suitability for multiple standards, has attracted attention for SDR. In the DCR, the signal is directly down converted to baseband, being then Low-pass filtered and sampled. Excluding signal amplifiers, usually before and after down-conversion, the architecture is as depicted in Figure 49.

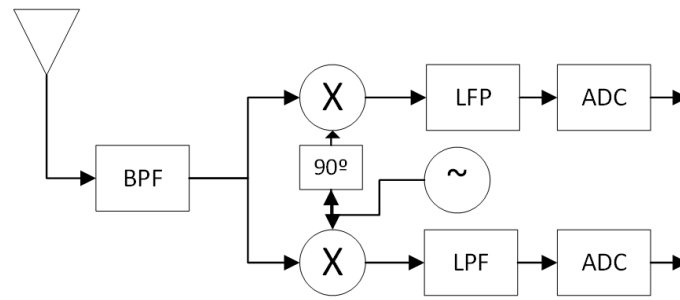


Figure 49 - Direct Conversion receiver architecture

DCRs typically perform sampling in quadrature and therefore implement two chains with Analog-Digital Converters (ADC's). The desired signals can later be selected by software filters.

DCR's are "tuned" to a certain frequency band of interest, which makes them flexible. However, changing the frequency of the oscillator takes a small period of time, which might be too long to cope with certain applications. Moreover, down-converting the signal directly to base-band induces phase noise from the local oscillator into the signal band. Therefore a very precise local oscillator, or later signal processing might be required to correctly recover the signal.

Tuned RF Receiver

The Tuned RF (TRF) receiver further simplifies the architecture by removing the analog down-conversion step. It performs analog-digital conversion of signal right after having passed a band selective filter (BPF) and therefore, disregarding amplifiers¹, consists of only 2 logical blocks.

Such architecture eliminates some of the shortcomings from the previous architecture, like the oscillator phase noise being coupled to the signal, but presents hard feasibility challenges. The main difficulty in creating a practical TRF receiver is the limitation of the ADC to handle high frequency signals in a wide frequency band. It must provide high sampling rates, usually in the order of tens of MHz to avoid strong aliasing, and cope with a dynamic range of about 100 dB (Reed, 2002). Such characteristics make the ADC - and therefore the DCR - difficult, expensive, and power-intensive. As so, in practice, the RF band filter is used to pass only a specific band of interest and remove strong interference signals, and subsequent filtering is employed in DSP.

¹ A Low-Noise amplifier (LNA) with automatic gain control is typically employed in both architectures before the ADC.

6.3 EXPERIMENT SETUP

Several experiments were carried which aimed at proving the viability of time-of-flight methods in the current scenario. Such experiments were two-fold:

1. Prove that the discussed phase-delay methods can be implemented in Software Defined Radio platforms, effectively providing high localization accuracy.
2. Prove that the chosen SDR platform and frequencies range are both compatible with the tunnel restrictions and the leaky-feeder network can effectively be used to propagate the signal and enable localization in the region covered by them. By using the leaky-feeder network, the devices can be installed in radiation-protected areas, being able to work without the risk of damage.

6.3.1 METHODOLOGY

A brief analysis of time-of-flight methods, as discussed in section 6.2.1, permitted the definition of hardware requirements, leading to the selection of the Universal Software Radio Peripheral (USRP) as the hardware component of the SDR system - see 6.3.2 for its description.

For development, the USRP was connected a standard Linux laptop, which controlled the unit and where the custom processing for the phase-delay algorithms was performed. The GNU Radio toolkit (Blossom, 2004; gnuradio.org, 2004) and the GNU Radio Companion (gnuradio.org, 2007) were used to implement the designed algorithms (see Figure 50), and the development could be incrementally done in short iterations alternating with testing.

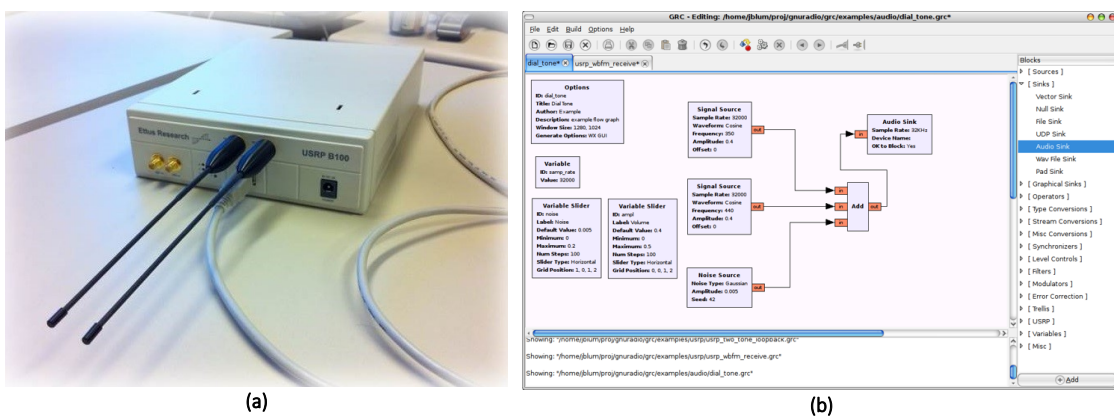


Figure 50 - The USRP B100 device (a) and a GRC workspace (b)

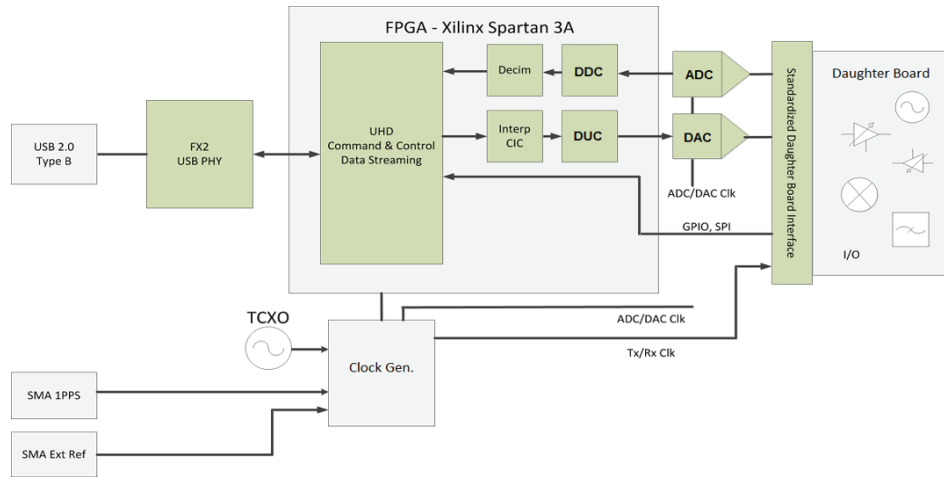


Figure 51 - The USRP B100 architecture

Most of development and testing was therefore performed in an ordinary office, except field experiments assessing the possibility of implementing the solution in the tunnel. Those experiments are described in 6.3.3.

6.3.2 THE UNIVERSAL SOFTWARE RADIO PERIPHERAL (USRP)

The Universal Software Radio Peripheral (USRP) is a device developed by Ettus Research LLC (ettus.com), which turns general purpose computers into flexible SDR platforms. Its architecture is based on a motherboard which provides computer interface, a programmable FPGA and connections for RF Front-end daughterboards. The main principle behind the USRP is that the DSP tasks are divided between the internal FPGA and the external host CPU. The high speed general purpose processing, like down and up conversion, decimation and interpolation are performed in the FPGA, while specific processing, such as modulation and demodulation, are performed at the host CPU.

For the current studies the USRP B100 was selected and equipped with the WBX daughterboard (Ettus_WBX). Figure 51 shows the architecture of the B100. It features 64 MS/s 12-bit ADCs and 128 MS/s 14-bit DAC (for both I/Q channels), a clock generator accurate to 2.5 ppm, and a programmable Xilinx Spartan® 3A 1400 FPGA which implements the default DSP, including Digital-Down (DDC) and Digital-Up Converters (DUC), decimators, interpolators and the communication interface to the host. In turn, the WBX daughter-board implements the RF front-end which has a bandwidth of 40 MHz in a frequency range of 50 MHz to 2.2 GHz. Communication to the host computer is done via a USB 2.0 interface, which allows up to 8 MS/s (complex domain).

The USRP B100 with the WBX board, despite being relatively low cost in its class, fulfils the project requirements, which were dictated mainly by the frequency range (VHF) and bandwidth - up to 2 MHz. Since the ADCs and DACs operate both in I and Q components one could guess it follows the architecture of a Direct Conversion Receiver, a fact that is proven by its components architecture (Ettus.com KB). Indeed, after receiving and amplifying the signal, the WBX down-converts it to in-phase and quadrature components and applies a 40 MHz low-pass filter (LPF)¹. Nevertheless, as discussed before, such architecture suffers from phase drifts being applied to the signal, which requires a careful assessment and compensation mechanisms.

6.3.3 MEASUREMENTS PERFORMED IN THE TUNNEL

Understanding if the tunnel and the leaky feeder network was favorable to the current methods was a key element in the study. For that step, after authorization to transmit was granted by the communications group (IT/CS), a 145 MHz wave was added to the leaky-feeder multiplexer at LHC Point 2. Over 100 m below, in the tunnel, a second USRP unit was installed which would measure the received signal - see Figure 52.

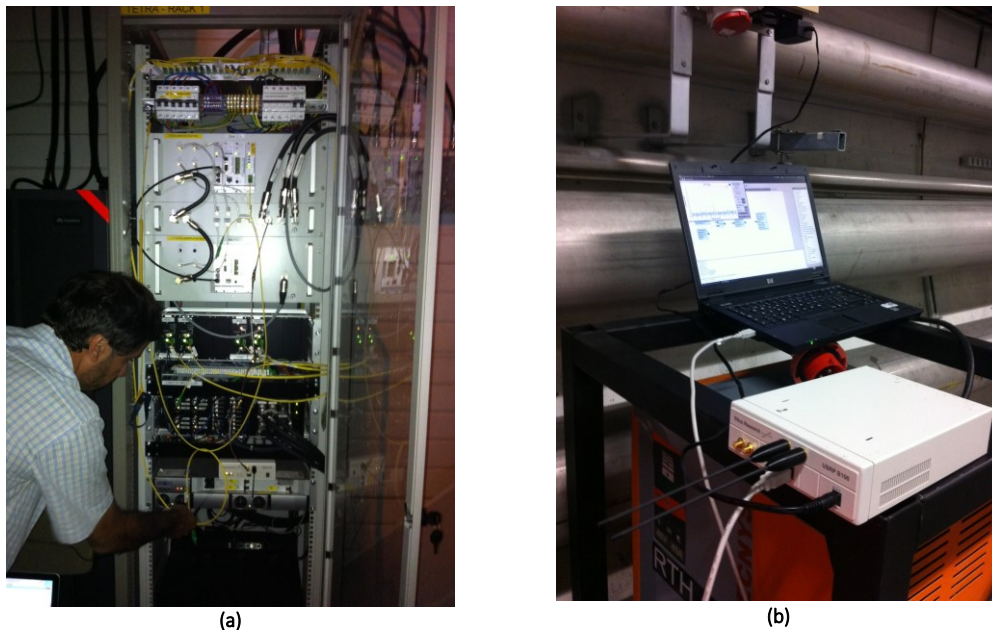


Figure 52 - Testing transmission of VHF waves in the tunnel with SDR
(a) Coupling signal to the leaky-feeder multiplexer at surface. (b) Underground receiving unit.

¹ The WBX transceiver implements the transmission chain following an identical architecture.

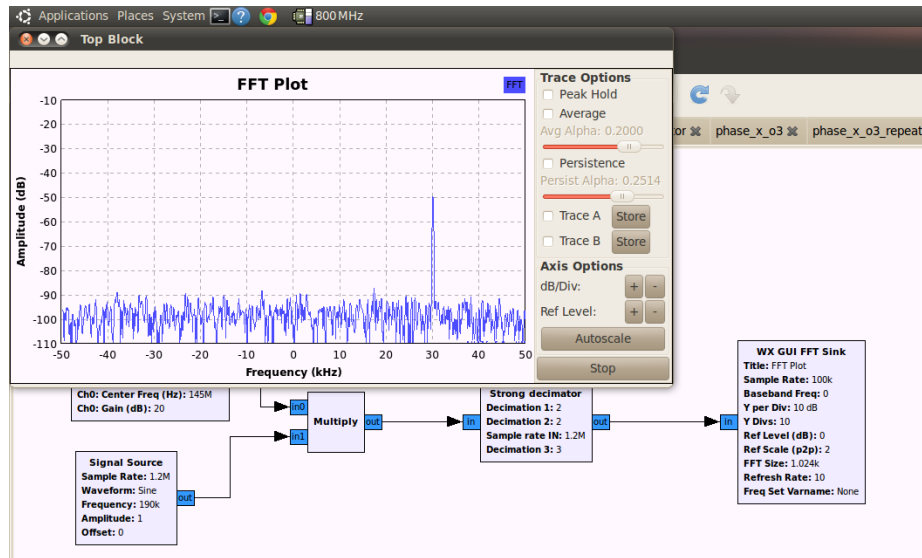


Figure 53 - Print-screen of the receiver unit, performing the signal FFT in real-time

The transmitted wave was alternating between two frequencies 30 KHz apart, which was a simple technique to make it unique and distinguishable from other signals eventually transmitted by existing equipment. At the reception, the SDR was tuned the carrier frequency and the signal sampled at 1.2 MS/s. After being strongly decimated it could be used to generate a live view of its FFT with 1024 points, updated at a rate of 10 Hz - see Figure 53.

In the FFT it can be perfectly seen two peaks of power, around -50 dB, alternating between 0 and 30 KHz. With a noise background of -90 to -100 dB that represents over 40 dB of margin to work with, which is quite good. Given that, at 150 MHz, the cable exhibits a longitudinal loss of 1.03 dB/100m (RFS World, 2010), the signal should reach tunnels regions 4 km away. Given that technical areas providing multiplexers are situated at least in every LHC access point, nearly every 3.5 km, the minimum required signal reach would be 2 km, and therefore the power achieved with SDR is sufficient.

Besides the fact that sufficient power arrives to the underground, it is impressive the low background noise level and the absence of other signals. This is, without a doubt, related to the fact that measurements are being performed in an underground tunnel, naturally shielded by earth from the surface signals.

6.4 DEVELOPED ALGORITHMS

Two algorithms were implemented, based on the principles of phase delay, in SDR. Typically, for most communication systems, SDR limits are imposed by bandwidth and CPU processing power. Nevertheless, when implementing localization systems, other parameters like jitter and clock stability become quite important. Since SDR platforms have not been specially conceived for localization purposes and are, by definition, more complex than specific-purpose hardware, these parameters might require special attention and turn out to be quite challenging.

6.4.1 DIRECT PHASE DETECTION WITH REFERENCE UNIT

The first algorithm to be explored implements a phase-detection system with reference unit (Pereira, et al., 2013), following very closely the drift-correction method (see page 123). An overview of the system architecture is given in Figure 54 and its main components are:

- **Rover unit (ROV)** - A moveable SDR unit whose location is to be determined. It implements the transmitter, which shall be simple for portability reasons.
- **Fixed Receiver units (FR)** - Units coupled to the *leaky-feeder* which receive signals from the Rover and Reference units and calculate the position of the first. They shall be installed so that full coverage is available in the concerned region, depending on the signal reach.
- **Reference unit (REF)** - The unit that generates corrective waves for compensation of frequency and phase drifts.

In the described design, all three entities are separated and FR units have to identify the Rover unit transmitting. Such problem is common between this architecture and its reversed

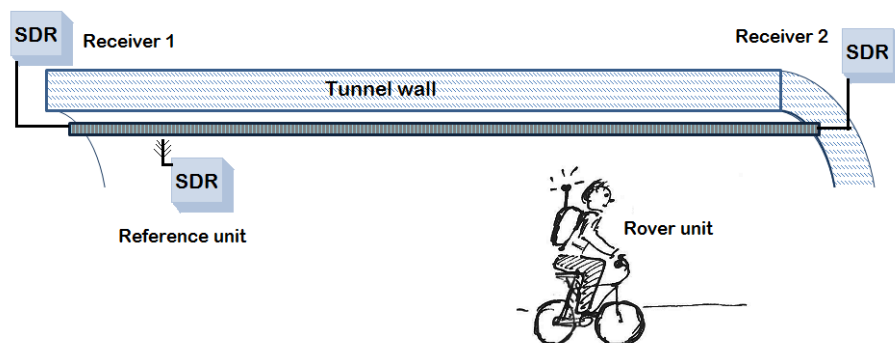


Figure 54 - Localization system with reference unit overview

version, where the rover unit would have to identify the “Fixed Transmitters”. In general, the reasons which favored this design are:

- **Keep the Rover simple.** DSP at high frequency can be expensive in terms of computational power and therefore become power hungry. Avoiding calculations of identification and position in the rover means it would be able to operate longer with battery, and eventually be implemented in the future as a very simple hardware device with high-autonomy.
- **Keep the reference unit fixed.** By principle, the reference unit must accompany the receiver. In a reversed design, it would need to be coupled to or implemented in the rover as well, translating into a complex equipment with high power consumption.

Spectrum allocation scheme

For the parameters of the communication it was established:

- **f_1 : 150 MHz** - The primary transmission frequency, in the VHF domain, allowing for 2 m localization range and ~ 10 cm accuracy.
- **f_2 : 151 MHz** - The secondary transmission frequency, for epoch disambiguation, enabling 1MHz differential and therefore localization within 300 m.
- **f_Δ : 10 KHz** - Frequency spacing to additional waves for corrective purposes.

There are several reasons behind a localization range of 300 m. On the one hand, given the limit 8 MS/s the USRP B100 can transfer via USB and the limited processing capacity available in the used laptop, it was set to use a frequency differential of 1 MHz, which would theoretically require a sampling rate of 2 MS/s. During testing it was found that, given that most of the whole signal band is hollow, by carefully choosing a different center frequency and handling signal images, one could reduce the sampling rate to 1.2 MS/s.

However, it was necessary to guarantee that phase detection could reach accuracies smaller than the epoch, i.e. below 2 m, which represents 0.5 % phase accuracy. Given that each wave occupies minimal band, the signal can be strongly decimated and filtered, reaching elevated SNR values. By applying moving averages (Watson, et al., 2002) it is possible to greatly improve the phase detection accuracy, a fact that is confirmed in the current scenario, where an average window of 100 samples was used.

Algorithm

As a prototype implementation, the configuration was simplified to a Rover (transmitter) and a combined Receiver-Reference SDR unit. Considering the latter receives the two initial frequencies, f_1 and f_1+f_Δ , the challenge is exactly on the creation of a stable corrective wave. Considering that the clock accuracy of USRP B100 is 2.5 ppm, and that the phase drift transfers to base-band, we might face frequency drifts up to 2.5×150 (=375!) Hz. Despite the quite technical background, the implementation is conceptually simple, the steps being:

1. Obtain f'_Δ as the difference between the phases of two incoming signals f_1 and f_1+f_Δ
2. Obtain $f_{r\Delta}$ as the phase difference between the corrective f_r and f_1+f_Δ .
3. Obtain $f_{\Delta\Delta}$ as the phase difference between f'_Δ and $f_{r\Delta}$, which represents an error function which must tend to zero.
4. Integrate the error function $f_{\Delta\Delta}$ over time, so that a corrective delta function $f_{r\Delta}$ smoothly converges.
5. Add phases of f_1+f_Δ and $f_{r\Delta}$ to obtain f_r , the corrective wave.

In order to verify whether the algorithm is working properly, it is enough to monitor the error function $f_{\Delta\Delta}$. When it converges and stabilizes at zero one knows that the delta signals are equivalent and the system is accurately emitting the corrective waves.

SDR implementation

When working with signals defined by complex samples, in order to create a signal representing the sum or difference of phases of two signals, the terms can be directly multiplied (to obtain sum) or the first term multiplied with the conjugate of the second (for difference).

Given the existence of blocks implementing such functionalities in the GNU Radio Companion (GRC) software, the previous algorithm might seem relatively straightforward to implement. However, it was found that, due to the large margin for frequency drifts - up to 375 Hz - the system was taking too long to stabilize and, often, it would not stabilize before a new drift occurred.

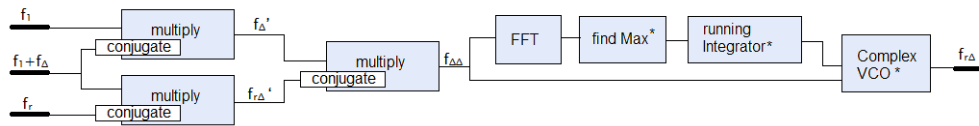


Figure 55 - Conceptual implementation of reference unit in direct phase detection

Due to that, a new design was investigated and implemented (Pereira, et al., 2013) which aims at achieving faster stabilization - see Figure 55. The implementation makes use of three new functional blocks (*findMax*, *Running Integrator* and *Complex VCO*) which had to be specifically implemented in C++ for the purpose. It takes the FFT maximum of $f_{\Delta\Delta}$, that is the frequency shift between the signals f_{Δ}' and $f_{r\Delta}'$, which is then passed to a running integrator, in order to converge to the exact frequency of $f_{r\Delta}'$. The frequency is then used by the complex VCO to create a wave in that frequency, and phase fine-tuning is achieved by directly considering $f_{\Delta\Delta}$.

6.4.2 ROUND-TRIP PHASE DETECTION

In a round-trip setup, the signal is originally emitted and finally received by the same unit, having a “reflection” unit in the middle. In such a design, the requirements for phase compensation are relaxed, since both original and delayed signals are bound to the same clock generator and therefore have perfect relative clock drift. For the current experiment the goal is to verify whether, in SDR, the signal phase does not suffer from distortions in the transmission and reception chains of both units and the phase-drifts applying in both directions of the same device are counter-compensated.

Algorithm

Even though the round-trip method is conceptually straightforward, it incurs an important difficulty: the wave can't be directly reflected. Doing so, being a continuous wave, it wouldn't be possible to distinguish it from the loopback path, in which the signal travels directly from the transmission to the reception circuits in the first unit. In order to tackle the problem it is required to separate the flows. Since time separation is not an option, and code-multiplexing would require the research of codes which would apply the same drift, two different frequencies had to be used. However, different frequency shifts are usually required in the units.

The key challenge behind such technique is to guarantee that any and every frequency shift is applied forth and back by the same clock generator.

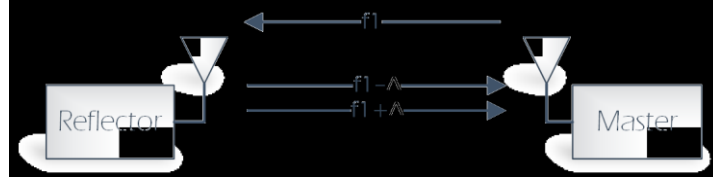


Figure 56 - Signals transmitted between Master and Reflector units
The master generates a wave of frequency f_1 , which is “reflected” in frequencies $f_1 - \Delta f$ and $f_1 + \Delta f$.

Let us consider a design where a wave is generated and analyzed in a unit, the Master, and reflected in another - the Reflector. If the wave has a frequency f_1 and is shifted by Δf in the Reflector then there would be no possibility to apply a perfect symmetrical shift when it comes back in the Master, since they are bound to different clocks. Having that in mind, a solution was achieved by employing two reflected waves with symmetrical shifts, as illustrated in Figure 56.

When the two reflected waves arrive back to the Master unit, after being shifted back to base-band, they will be affected by the difference of the clock drifts. Nevertheless, given that they suffered symmetrical shifts, the two waves can be combined so that the shifts cancel, as:

$$\begin{cases} \varphi_1(t) = [f_1 - \Delta f_R + \Delta f_M](t - t_0) \\ \varphi_2(t) = [f_1 + \Delta f_R - \Delta f_M](t - t_0) \end{cases} \quad (\text{eq. 6.8})$$

Where φ_1 and φ_2 represent the phase functions of the signal of original frequency f_1 , after being shifted $\pm \Delta f$ in the Reflector (Δf_R) and $\pm \Delta f$ in the Master (Δf_M). Δf_R and Δf_M are not exactly equal due to clock drifts, so their difference is represented by ψ .

$$\begin{cases} \varphi_1(t) = [f_1 + \psi](t - t_0) \\ \varphi_2(t) = [f_1 - \psi](t - t_0) \end{cases} \quad (\text{eq. 6.9})$$

After demodulating by f_1 , it becomes straightforward to cancel out the frequency due to clock drifts differences ψ , achievable by simply summing or averaging the expressions. Without a time-dependent component, only the space-dependent component (distance) matters to the phase. In order to keep the same ratio between phase and distance, the average is preferred over the sum when merging the signals.

SDR implementation

A simplified block diagram of the implementation of the algorithm in SDR is shown in Figure 57, where the steps are:

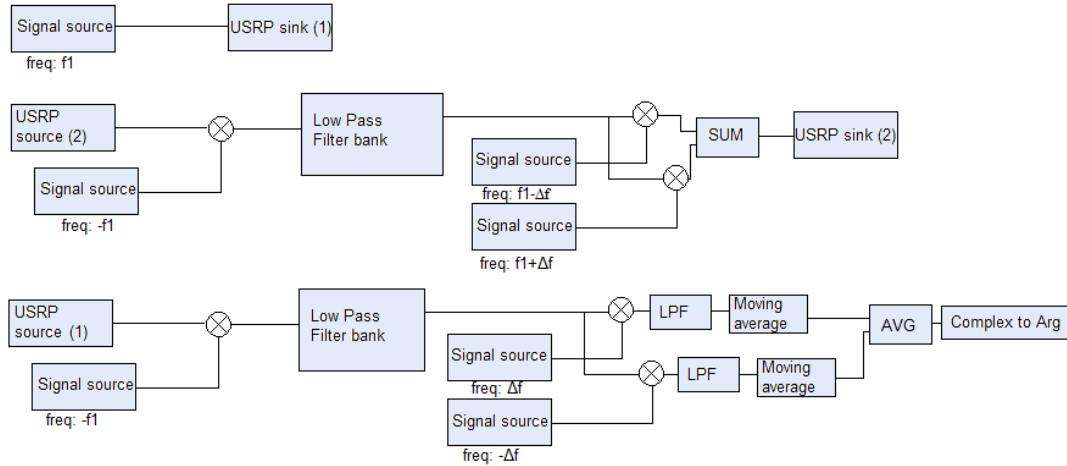


Figure 57 - Conceptual implementation of the round-trip phase detection method

1. A wave of frequency f_1 is immediately sent out to air. The applied “shifts” are $[f_{1M}]$.
2. A second unit captures it (USRP source 2) and shifts it back to 0 Hz. Note: It is natural that the wave is not exactly at 0 Hz due to the different clock drifts which affect both the carrier frequency and the f_1 demodulation frequency. Shifts: $[f_{1M}, -f_{1R}]$.
3. The resulting wave is low-pass filtered and multiplexed into two frequencies $f_1 - \Delta f$ and $f_1 + \Delta f$. Shifts: $[f_{1M}, -f_{1R}, f_{1R} - \Delta f_R]$ and $[f_{1M}, -f_{1R}, f_{1R} + \Delta f_R] \Rightarrow [f_{1M}, -\Delta f_R]$ and $[f_{1M}, +\Delta f_R]$.
4. The initial unit receives the signals and shifts down from f_1 . Shifts: $[f_{1M}, -\Delta f_R, -f_{1M}]$ and $[f_{1M}, +\Delta f_R, -f_{1M}] \Rightarrow [-\Delta f_R]$ and $[\Delta f_R]$.
5. The signals are independently shifted, down and up, by Δf . Shifts: $[-\Delta f_R, \Delta f_M]$ and $[+\Delta f_R, -\Delta f_M] \Rightarrow [\psi]$ and $[-\psi]$.
6. The signals have now perfectly opposite shift distortions. Since the absolute frequency value shall be very small¹, a moving average is applied for smoothing and finally the average is taken to get the central constant value.

After an initial calibration at position 0, distance between the units will incur a signal propagation delay measurable by a proportional phase shift. For reference, the diagram of the full GRC implementation can be found in 0.

¹ With a 2.5 ppm oscillator accuracy, a 10 KHz wave will have up to $2.5 \times 0.01 (=0.025)$ Hz error.

6.5 RESULTS

Considering phase delay methods as the ones presented in this study, the phase stability is a critical parameter of the system which determines its feasibility. Since it can only be achieved when stabilization or compensation methods are working 100% correctly, the phase stability was considered to evaluate the methods and, by using the plotting tools of the GRC software, it was checked, in the first place, for variations over the time.

6.5.1 DIRECT PHASE DETECTION METHOD

In the direct phase detection method, which uses a reference unit, the system would ideally converge to 0-frequency 0-phase in very few seconds. Such convergence would be possible even in the case of some changes in frequency, as long as they were progressive but rarely abrupt. However a difficult scenario was found with the SDR, breaking these conditions. Fast and significant changes in frequency were found to happen, like those observed in Figure 58. They were very significant in terms of frequency drift, typically by 30 Hz or more, and very frequent, happening between every 1 to 5 seconds.

From the plot, one can also notice that, despite these frequency changes, phase continuity is kept, which indicates that frame dropping was not the issue. In order to isolate the problem, instead of a SDR unit emitting the original wave, a dedicated RF wave generator was

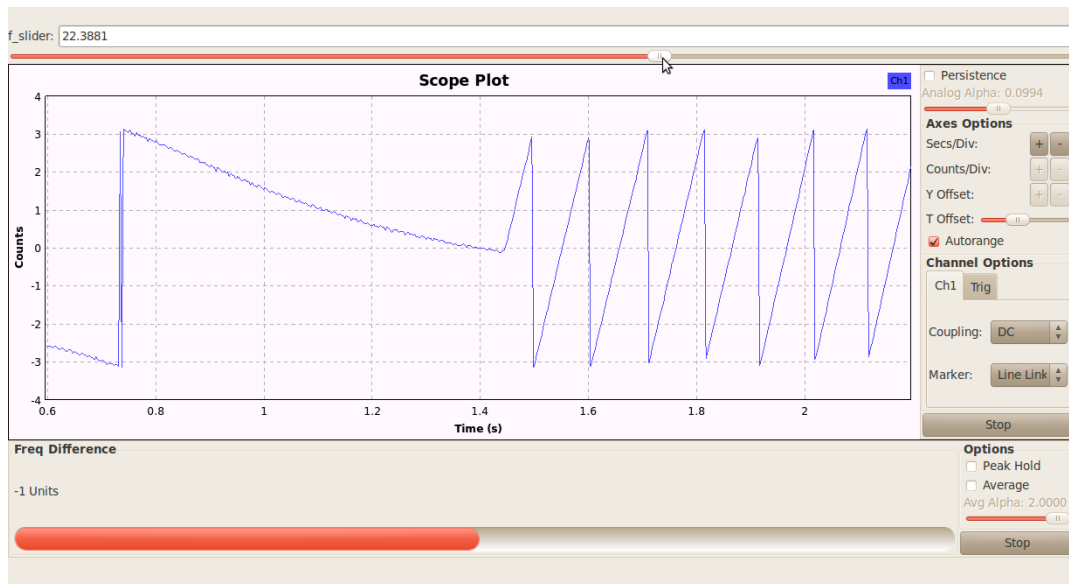


Figure 58 – Phase stability of the direct phase detection method

used. As a result the signal showed to be remarkably stable, eliminating the mentioned frequency hopping phenomena almost completely. This fact strongly indicates that, at some point of the transmit chain of the SDR, the signal suffers strong side effects which are not directly proportional to the oscillator. This might be due to some components being highly sensitive to the clock changes eventually at the level of the FPGA, or de-synchronisation happening among the processing layers, introducing little frequency hops in the resulting wave.

Even considering the fast-convergence implementation of method, which needed a few seconds to stabilize, such behaviour of the SDR reduced to zero the available time-window of stable system and turned the method virtually helpless for localization in the current scenario. Given the complexity of the SDR system, these issues represent a major obstacle whose resolution is outside the scope of this thesis. Therefore alternative methods were investigated.

6.5.2 ROUND-TRIP METHOD

The second method, based on the round-trip principle to avoid clock synchronization issues, was evaluated in a very similar way. After implementing the model, step-by-step tuning of frequencies and filter parameters was performed and quite interesting results could be observed.

In the current setup, after being “reflected”, the signal could be recovered in the original unit and, after being shifted to 0-frequency, it would behave well, without presenting any kind of frequency hops – see Figure 59. Although sensitive to interference of nearby bodies, when performed basic smoothing using a Moving Average filter, the phase would remain impressively constant while perfectly responsive to distance changes.

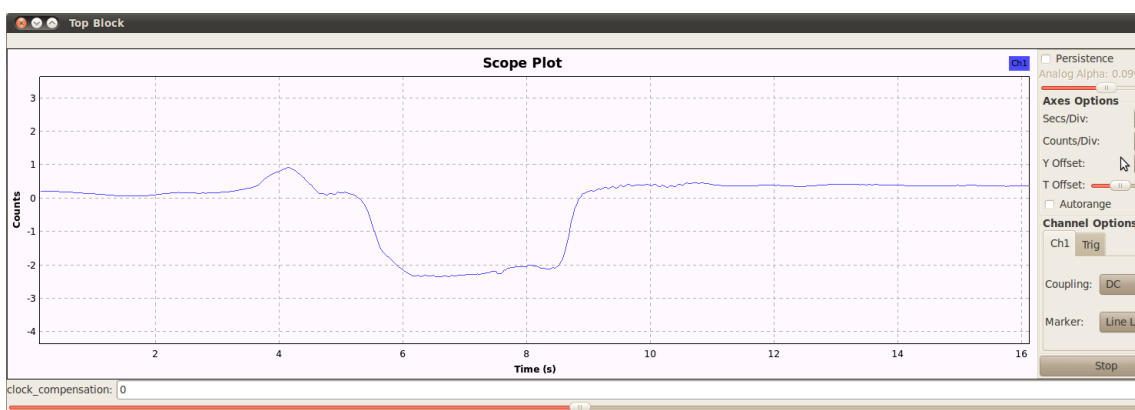


Figure 59 – Phase stability of the round-trip method

In Figure 59 it is possible to observe the evolution of the signal phase over a period of 16 sec. After second 5 one unit was moved by nearly 40 cm, kept there for 2 sec and then rapidly moved back to the original position. Indeed, in a round trip configuration at 150 MHz over air (2 m wavelength) a complete period (2π) shall occur with 1 m displacement. A 40 cm change should therefore incur a phase delay of 2.5 rad, which is approximately the observed value.

The results obtained in this test provide a strong argument that, despite the transmission inconsistencies found with the previous model creating a “frequency hopping” behavior, those effects are similarly affecting the transmit and receive chains of the SDR and therefore, by carefully employing round-trip techniques, they can successfully cancel out. Furthermore, it is quite remarkable that, at sampling rates higher than 1 MS/s, there would be no frame dropping and both receive and transmit chains would remain perfectly aligned, yielding a very stable phase.

6.6 ASSESSMENT ON A COMBINED LOCALIZATION SYSTEM FOR UNDERGROUND TUNNELS

The reasoning behind creating a localization system composed of two subsystems, each using a distinct technology, builds upon meeting several requirements found for the current scenario, among them:

- Enabling localization in very long areas without immediately incurring considerable financial investment.
- Be simple and resilient, even if performance has to be compromised, so it can be relied upon for critical services, including safety of personnel.
- High accuracy is desirable, but not strictly necessary in the whole range.

Even though RSSI fingerprinting did not achieve the meter-level goal, it fulfils the aforementioned requirements and was found to be an excellent answer to the problem, considering that accuracy could be improved with a second technology where strictly required. Consequently, research on the RSSI fingerprinting and subsequently on the phase-delay system was endeavored.

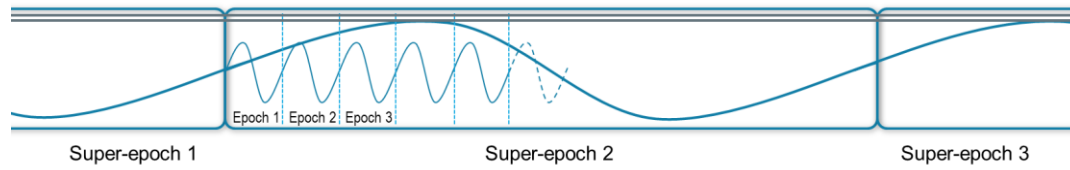


Figure 60 – Schematic of epoch and super-epoch disambiguation

6.6.1 SYSTEM INTEGRATION

In the context of a long underground tunnel, the installation of the high accuracy fixed units, besides economic reasons, will be possible only every few kilometer where access to protected technical areas, usually at surface, is possible - in the case of the LHC they are located every two kilometers. For that reason, the higher-accuracy system requires a position reference with an accuracy better than its range, preferably around 100 m. Such position reference can therefore be provided by the first localization method based in RSSI.

Combining calculations

The design of the phase-delay system, as seen before, considers a second set of frequencies for cycle (or epoch) disambiguation. According to the proposed design, the selected frequencies - 150 and 151 MHz - allow for a localization range of 300 m, being 150 m in the round-trip design.

In order to calculate the final absolute position, the system must translate the relative high-accuracy position to an absolute one, which requires a static referential. Since no system can provide a precise location directly serving as a reference, the solution is to consider the range of the system as a region – called super-epoch – which can be identified by obtaining a location estimate from the fingerprinting system. A diagram of the regions can be found in Figure 60.

From the figure we can see the base regions – epochs – where localization is accurate by using a 150 MHz wave. Epochs are, therefore, two-meter long. To distinguish between epochs the 1 MHz wave is used and, therefore, a new large scale epoch –named super-epoch – of 300 meters is defined. To go beyond that range and disambiguate between super-epochs, we must consider the approximate position found with the RSSI fingerprinting method. Since the method finds a position with an accuracy in the range of 50 meters, disambiguation becomes undoubtedly possible.

As an example, let us consider that the system is aligned to the metrical marking of the tunnel, so that at position 0 m we have phase 0 in both phase-measurement systems, and the case of using the system and obtain the readings: $\pi/2$ rad for the 150 MHz wave, $3\pi/2$ rad for the 1 MHz one, and an absolute metrical position of 2060 ± 50 m from the fingerprinting method. Translating the distance to epochs, one finds that the location should be between super-epoch 7 (at 70% of its length or 210m) and super-epoch 8 (at 10 m relative to the beginning). A measurement of $3\pi/2$, which translates to 225 m ($3/4$ of 300 m), lies undoubtedly in the region selected by the first method and helps confirming we are in super-epoch 7. The same principle applies to the next stage. Knowing that $3\pi/2$ is 75% of the length, we end up in the middle of the epoch 113 ($300 \cdot 0.75/2$). A measurement of $\pi/2$ rad for the 150 MHz wave represents 0.5 m (25% of 2 m). The final position is therefore given by $(7-1) \times 300 + (113-1) \times 2 + 0.5 = 2024.5\text{m}$ (± 10 cm considering a phase accuracy of 5% at 150 MHz).

Physical integration

Despite being two independent technologies, the need for combining results from both systems motivates the development of an integrated unit. Moreover, factors as the relatively simplicity of both methods, the high performance of programmable hardware – including FPGAs, and concerns on power-consumption, strongly favor an implementation further integrated into a single combined unit.

Even though an analysis on the implementation of the system is outside the scope of this thesis, a potential architecture is mentioned for the purpose of better illustrating applications. In an integrated design, the Rover must implement receivers in the GSM, WLAN and VHF band, transmitters in VHF and a GPRS communication module to transmit the location. Besides the Rover, Transmitters and Reference units are required in the areas where high-accuracy is intended.

6.6.2 ADVANTAGES OF MODULARITY

Despite the fact that the combination of systems was necessary, there are several advantages from such a modular architecture. Having both systems decoupled makes each one simpler and less prone to problems. Furthermore, there is a considerable improvement with respect to flexibility, as it can be better customized to applications having different needs, eventually requiring a single localization technology.

A summary of the advantages, from a System and User perspectives, is given below.

System perspective

- **Simplicity** – Each component is less complex and can be developed independently.
- **Robustness** – Each component is simpler and therefore more robust. The inherent robustness of the fingerprinting-based system is saved which is especially important to make it suitable for safety and rescue purposes.
- **Flexibility** – Depending on the application, low-accuracy in a long range or high accuracy in a short range can be independently employed as well, translating into cost-effective solutions.

User perspective

- **Cost-effectiveness** – Besides solutions comprising a single system, the long-range coarse localization system can be progressively upgraded to high-accuracy in areas where it is justified.
- **Higher-Availability** – in case of maintenance of the high-accuracy system, eventually more common given its higher degree of complexity, lower-accuracy localization and dependent processes, especially critical ones, shall not be affected.

6.6.3 APPLICABILITY - POSSIBLE USE CASES

The researched solution targets the case of the LHC tunnel which, despite representing a rather unique environment housing a particle accelerator, has requirements that can surely be found in many other situations. To recapitulate (from Table 2, page 49) some of the key target characteristics:

- Accuracy: regularly 10-50 m, up to 1 m in special areas.
- Range: tens of kilometers (27 in the case of the LHC).
- Output data: 1D position.
- High availability (>95%) and Robustness.
- Infrastructure: no devices shall be installed in the area.
- Cost: relatively low, upgradeable.

Such characteristics are easily found in mines and other tunnels where hazardous activities are carried out. Especially in those cases, where emergency management and rescue are extremely important activities, there haven't been solutions that respect the required robustness while enabling for high-accuracy where required.

Despite being designed for radioactive and hazardous tunnels, the developed solution is a highly promising answer to many other scenarios:

- **Road tunnels** – Long roadway tunnels, which are commonly used to transverse mountain regions, typically dispose a radio communication infrastructure using leaky-feeder, and therefore localization could be introduced with minimal cost.
- **Building connection paths and city undergrounds** – In some industrial complexes and cities, where underground tunnels connect buildings or are used for telecom, power and sewage services, localization might be of extreme importance for e.g. safety purposes. In order to meet harsh conditions, like dirt and humidity, a solution based on a single radiating cable might be among the best and only possibilities.
- **Tracking of important objects in logistic centers, airports and industrial lines** – Considering complex logistic routes for, e.g., goods in a logistic center, luggage in airports, products in a factory, it is conceivable to deploy a radiating cable along the lines. By installing receivers on important objects, they can be tracked so that their routing is guaranteed, avoiding loss and meeting the best delivery timings.

In turn, a localization system uniquely having a high accuracy-component, even though it was not designed with such objectives, can also be of interest in diverse situations, including:

- **Tracking in corridors** – Whereas people or moveable objects are to be tracked or informed of its position, a single *phase-delay* system can provide an accurate tag in a relatively long section, up to 300m. Instead of using *leaky-feeder*, such a system can be composed of units emitting RF to air directly.
- **Industrial alignment** – Considering a hall or corridor where pieces of machinery or equipment are to be installed at relatively precise places, fixed units can be attached to a wall and distance can be obtained with the rover units. By employing a second set of fixed units in a perpendicular wall, 2-D coordinates might be achieved for wide spaces.

6.6.4 SCIENTIFIC VALUE

Even though *leaky-feeders* are commonly found in mines and tunnels, maybe due to the low attenuation levels found with such cables, no underground localization solution was found to take advantage of GSM or even proprietary signals by using fingerprinting. In the current research work it was found that, despite the limitations, such methods yield reasonable accuracy which is suitable for safety purposes and to serve higher accuracy methods by identifying a region.

One of the major knowledge advances yielding from the current study is the proof that, even under very tight budgets and engineering resources, it is possible to deploy large scale localization systems that even comply with challenging scenarios and retrofit in existing installations. To date and to the knowledge of the author, there is not any hardware device capable of performing fingerprinting which is flexible enough to work with a range of network technologies and eventually to allow for selecting radio-frequency within a considerable band. The implementation of such a device, despite conceptually simple, could be a significant milestone in providing localization services in scenarios which had never been considered before. Furthermore, the possibility of enhancing the accuracy where necessary by installing fixed hardware units is a novel concept which brings more flexibility and increases possibilities and cost control.

A slight discovery originating in the current research work was the verification that signals propagating in the same direction in a *leaky-feeder* cable will exhibit a remarkably identical power profile – see section 4.2.4. Unfortunately, such phenomena didn't occur in signals propagating in opposite directions, which prevented the ICRD method from yielding better results.

As a last point, even though less significant, we believe that the thorough investigation of the background theoretical concepts from dozens of sources allowed the author to compile the relevant subjects in a condensed yet comprehensive and logically-structured way.

6.7 CONCLUSIONS

This chapter presented the studies on localization techniques for accurate positioning in the CERN tunnels, and its feasibility using Software-Defined-Radio (SDR) platforms. Two narrowband approaches, based on the principle of Time-of-Flight, were investigated. On the one hand, one approach uses direct-phase detection with a synchronization signal, requiring very simple Rover units. On the other hand, a round-trip approach relaxes the need for synchronization but requires the clock shifts to be perfectly symmetrical. Moreover clock *jitter* and *frame-dropping* must stay within acceptable limits.

Tests using the USRP B100 and GNU Radio showed that the first approach could not achieve the expected behavior since the signal was recurrently being affected by fast frequency shifts which could not be compensated within the available time frame. In turn, the round-trip approach showed to perform quite well, as the effects introduced in the signal along the transmit chain of the SDR were cancelled out when also passing through the receive chain of the same device. Relative movement of the units among each other could therefore be perfectly observable, as the measured phase change correctly represented the displacement.

In the last part of the chapter, an analysis of the complete system if performed. Being composed of two sub-systems, the proposed solution has inherent advantages from both the development and end-user perspectives, like simplicity, robustness and added flexibility, making it valuable for different scenarios including safety in tunnel roadways and city undergrounds, tracking of objects in logistic centers and airports, and alignment in industrial contexts.

CONCLUSIONS

This thesis presents the research on localization techniques targeting a very unique underground environment - the accelerator tunnels at CERN, specifically that hosting the Large Hadron Collider (LHC). The specific nature of these tunnels where bulky metallic equipment and panels are present, together with the ambitious goal of providing high accuracy localization in an environment with very rigid and restrictive deployment regulations for equipment, were the foundation of a singular problem. This unique setting presented an exciting challenge which had to be tackled.

Despite the existence of extensive literature for indoors localization, there's very little research on underground localization not requiring specific infrastructure, the most relevant publications investigating WLAN over *leaky-feeders* in a short tunnel section. Building on the same idea, several experiments were conducted in the current tunnel in order to characterize and exploit the existing signals, namely GSM and WLAN, for localization purposes. The detailed characterization of the signals received power (RSSI), presented in Chapter 4, shows that the attenuation of the GSM signal, despite being in tight agreement with the cable specification (around 3 dB/100m), suffer from significant variations. Discrepant values, up to 10 dB, are found for the same point among different measurement sessions or slightly different measurement conditions. Indeed, when there was somebody nearby or the distance between the cable and the antenna changed, the RSSI would considerably be affected, up to 20dBs in the latter case. It was also verified that the RSSI could increase or decrease non-uniformly in subsequent measurement points, a situation where analytical method become particularly ineffective. In a more detailed scan, in which a third GSM channel was detected, it was found that the power profile among the two channels propagating in the same direction was very similar, with a spearman rank-order coefficient up to 99%. When carrying out experiments with WLAN, in a setup involving two access points installed 150 m apart, it was verified that the longitudinal attenuation is much higher, in the order of 14 dB/100m, and RSSI differences among the several sessions much smaller, typically less than 3 dB - a condition that is expected to favor localization.

Considering that the measurement could be performed in reasonably similar conditions, and that each position is, to some degree, unique, empirical methods show up as an attractive yet simply approach for localization. RSSI fingerprinting methods are explored in Chapter 5, with several KNN variants in different configurations being tested. With GSM it was verified that, under optimal conditions, i.e., when the measurements belong to the same session, NN could yield exceptional results, finding the correct point 86% of the cases. However, under more realistic conditions, i.e., when obtaining the online fingerprint from another session, the values drastically drop reaching the same probability only with KNN, $K=5$ and an error-distance of 80 m – these two cases can be graphically viewed in plots E and F from Appendix C. In order to improve on these performance figures, several approaches were explored. Among the most significant, by merging the *radio-map* from several sessions one can reduce the error-distance to 60 m, and if one can further merge the online fingerprints the error-distance gets as low as 40 m at 90% confidence. In another plane, a new weighting method to KNN was developed, which attempts to consider the reliability of a measurement from its standard deviation. The results are very positive, and show an improvement in the whole error-distance domain, up to 27% (both cases using a merged *radio-map*). Furthermore, by taking advantage of channels power differential, the ICRD method was developed which doesn't consider the absolute power anymore. Therefore, despite exhibiting similar performance, it is expected to reduce the need for calibration. Moreover, to better understand the limitations, an ideal KNN was modeled and tested with GSM. It was found that the exact match is very often not within the K selected results and therefore, to further improve the accuracy, more sources of information would be required.

Tests with WLAN revealed much more expressive results. Without optimizations, it can achieve 30 m of distance-error in 91% of the cases. Consequently, a multi-technology method was developed to take advantage of the several available signals. Tests with GSM and WLAN together revealed that the performance would just be coincident as with WLAN alone, as they unfortunately exhibited very different performance levels. However, the deployment of WLAN in the LHC is only possible during extended maintenance periods, since off-the-shelf APs would suffer permanent damage if exposed to the radiation of a high-energy accelerator in operation.

Given the impossibility of further improving the accuracy with RSSI fingerprinting methods, a complementary system, based on the principles of TOF, was investigated. Meeting the tunnel restrictions and leveraging the existing VHF network, a phase-delay measurement system with synchronization units was developed and considered as a second stage of the localization where high-accuracy is required. From the implementation in SDR one could learn

that frequency shifts, stemming from its Direct Conversion Receiver architecture, occur frequently, making synchronization between units extremely difficult. A second approach, following the radar principle, is then explored and an algorithm for counter-compensating random phase-shifts is developed. The approach proves to work well even with SDR devices and displacements among the units can be precisely measured.

As a solution being composed of two sub-systems, it shows advantages from both the system and end-user perspectives, including simplicity, robustness and added flexibility. Besides its application in the challenging environment of a particle accelerator tunnel, the technology is shown useful in many other contexts, like safety in tunnel roadways, tracking of objects in logistic centers and airports, and alignment in industrial halls.

THESIS CONTRIBUTION AND ACHIEVEMENTS

The RSSI fingerprinting and phase-delay systems, even though they were tested separately and are in an investigation state, were conceived to work together. RSSI fingerprinting was proved to work sufficiently well for coarse localization, with accuracy around 50 m, which would enable for safety purposes, including finding people in case of emergency. The fact that the system is totally passive and uses GSM which is considered a safety system with fail-safe mechanisms, makes it very robust and ideal for safety. In areas where accurate localization would be needed or worth the investment, the second level of localization could be enabled by installing the necessary equipment in the respective surface cell. Even though the joint high accuracy system could not be experimentally tested in the tunnel due to reasons of access limitation, the experiments support the validity of the theoretical model and therefore a careful integration, especially if implemented in dedicated hardware, would achieve the desired outcome.

Besides serving as a solid basis for a possible implementation in the LHC tunnel, this thesis presents an important contribution to the understanding of the signal properties and localization in harsh tunnel environments. Among the main topics, (1) the characterization of the signal propagating over leaky-feeder, (2) the power profile analysis and observation of the ICRD properties, (3) the development of KNN variants in a generic location fingerprinting framework and (4) the design and development of an high-accuracy localization system using Software Defined Radio developed knowledge (including IT tools) which is expected to be an important reference for new studies and localization systems in similar underground environments, where the existing or eventually undisclosed information is virtually inexistent.

FUTURE WORK

Even though the concepts developed in this thesis were thoroughly analyzed and tested, there's a wide range of possibilities where further advances could be investigated and implemented. In the first place, RSSI fingerprinting methods could be explored with filtering techniques, e.g. employing *Kalman* or *Particle filters*. Even though preliminary studies in that direction were made, the results didn't yield the desirable performance gains, sufficient to avoid a secondary system. Furthermore, given that those methods are already well-known in literature they were not further investigated in the context of this thesis. Regarding the phase-delay system, further development could be done in order to allow for communication between the Rover and Fixed units or even among Rovers, which would allow to share the location with, e.g., the central.

From the perspective of implementation, despite not directly related to a PhD work, there are a number of challenges that would need to be tackled by a team of software and hardware engineers. For instance, to improve the sending and receiving of signal via a single medium – the leaky-feeder – and avoid saturation of the receive chain, it is important to reduce the feedback loop. Circulators are a technology that can be employed for the purpose and could be tested in the existing scenario. Also, the Rover unit would eventually work best as a combined GSM and VHF transceiver with a control module implemented in, e.g., an FPGA. As so, efficient power consumption and high portability would be possible while avoiding the limitations of SDR, while the combined logic would take care of determining the “sector” using RSSI fingerprinting and, where available, use the high accuracy infrastructure to find the precise location.

FINAL WORDS

Location techniques, in particular those based in fingerprinting, are a hot research topic nowadays. A lot of investigation has been put towards the application of these methods to the most diverse areas while improving their accuracy. Location finding has become ubiquitous, serving the most diverse areas, from game-playing to disaster management.

The development of this thesis work, and specially its writing, besides the additional knowledge it might have brought to academia, was an experience with profound repercussions to the author's scientific and personal mindset. Perseverance was probably one of the most crucial attitudes developed throughout the work and which was sustained by two pillars: the motivation of contributing to such an extraordinary field, and the people who helped creating the beautiful research environments I took part in.

W-KNN VARIANTS RANKING SESSION

```

1. In [55]: %run gsm_method1.py
2. Parsing LHC_1Fev_Alice
3. Started 2011-02-01 11:16:11.293783
4. Parsing LHC_2Fev_Alice
5. Started 2011-02-02 11:26:27.121886
6. Parsing Third measurement in Alice to Atlas section
7. Started 2011-02-08 15:26:32.981409
8. Parsing LHC_4th_tw_atalas.gdat
9. Started 2011-02-10 14:44:38.250971

10. Testing with function mean
11. [[[ 6  1 42  9 35 93 92 158 325 200 153 111 65 47 77 15 11]
12.    [ 5  1 44 12 33 95 91 155 327 198 157 108 63 47 77 16 11]
13.    [ 4  0 42 17 91 108 111 136 281 158 115 89 35 41 52 49 51]
14.    [ 4  0 40  4 55 85 102 171 328 168 130 85 24 30 53 51 50]]]

15. [[ 0  8 53  2 42 77 91 172 310 207 132 119 65 47 88 14 13]
16.   [ 0  8 52  2 43 77 89 173 309 208 132 120 65 47 88 14 13]
17.   [ 0  9 44 12 57 75 83 199 286 187 130 71 33 29 62 52 51]
18.   [ 0 11 47  8 61 64 74 187 304 195 131 103 46 38 77 34 32]]]

19. ### Final result ###
20. [[ 164.14738088  166.18146579  162.48512492  162.42321648]
21.   [ 175.4241612  175.92125117  170.78539362  172.08111463]]

22. Testing with function max
23. [[[ 7  4 37 10 55 79 89 195 297 170 159 114 70 60 73 14 7]
24.    [ 7  3 35  8 55 74 86 187 305 171 165 115 72 60 73 14 10]
25.    [ 3  0 47 25 65 92 130 164 265 148 107 81 52 48 54 48 51]
26.    [ 6  0 38 18 63 72 116 194 309 162 104 74 34 37 56 47 50]]]

27. [[ 0 19 37  0 64 89 86 177 280 194 158 97 65 61 88 15 10]
28.   [ 0 19 37  0 62 89 88 170 288 192 158 98 64 62 88 15 10]
29.   [ 0 17 47 15 63 74 101 182 300 164 114 56 40 41 68 48 50]
30.   [ 0 18 36  9 59 74 89 176 302 185 149 88 38 39 71 34 34]]]

31. ### Final result ###
32. [[ 163.12937396  165.1432054  161.48421597  161.68979226]
33.   [ 171.80535423  172.64220009  169.51352174  170.84415312]]

```

NOTE: The intermediate tables represent the error histogram, where each bin represents one calibration point distance-error, from -8 to 8. The final result table shows the ranking scores.

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SCORE TO RELATIVE FUNCTION

```
1. def score_to_relative( results, weights=None ):
2.     """ Calculate the relative (inc cumulative) scores of a result set.
3.     Weights can be provided to be applied to the relative result
4.     """
5.     assert weights is None or len(weights) == len(results), "Size mismatch"
6.
7.     tot = .0
8.     parts = []
9.     for i, resu in enumerate(results):
10.         value = float(resu[1]) if resu[1]>.1 else 0.1 #Avoid div by 0
11.         weight = float(weights[i]) if weights is not None else 1.0
12.         part = (1.0+weight)/value
13.         parts.append( part )
14.         tot += part
15.
16.     out = []
17.     cumulative = .0
18.     for i, resu in enumerate(results):
19.         rel_score = parts[i] / tot
20.         cumulative += rel_score
21.         out.append( resu + [ rel_score, cumulative ] )
22.
23.     return sorted( out, key=lambda x: x[2], reverse=True )
```

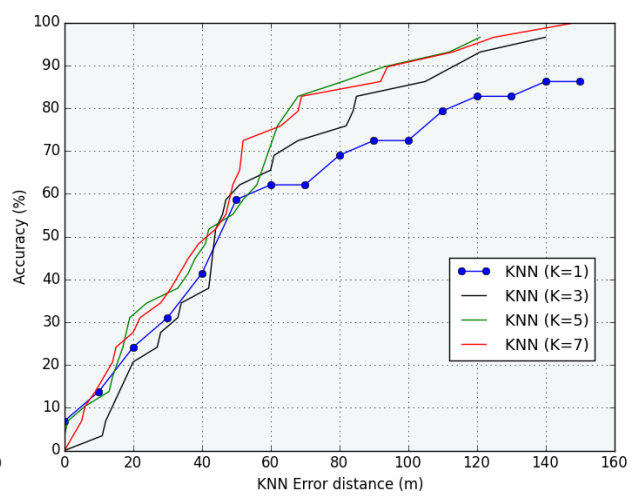
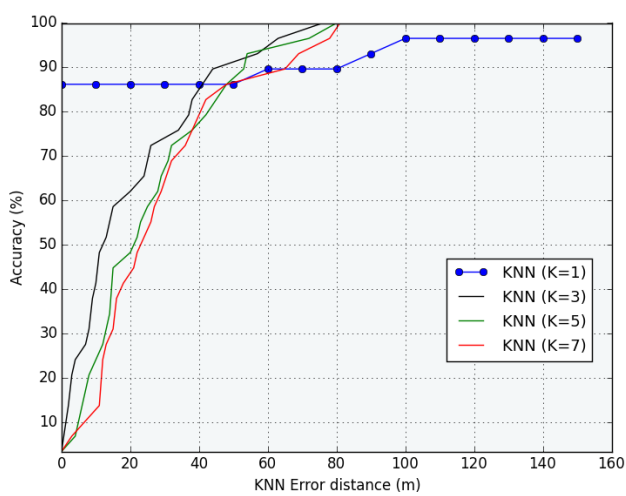
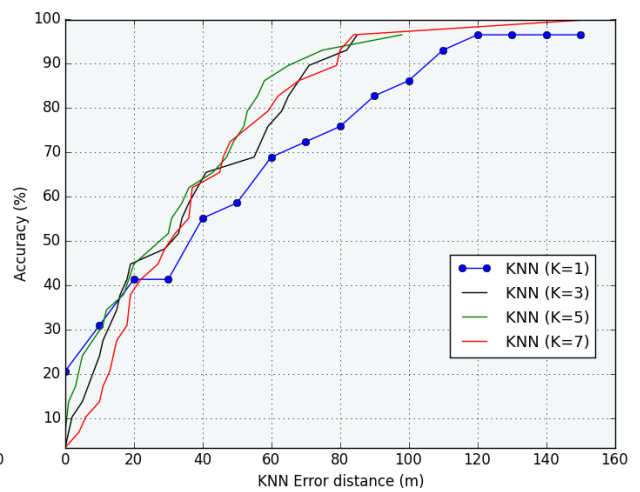
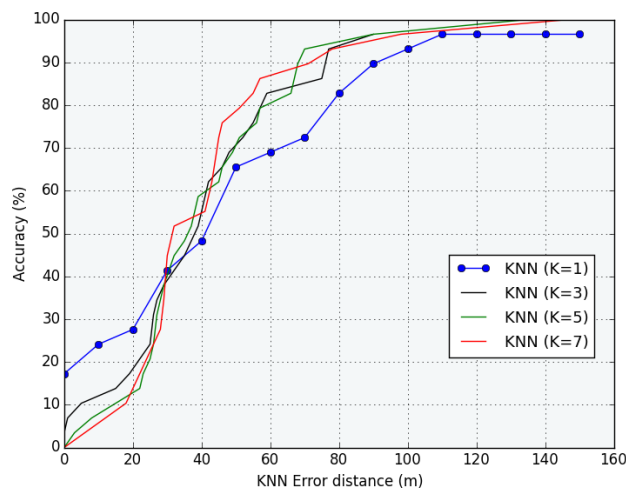
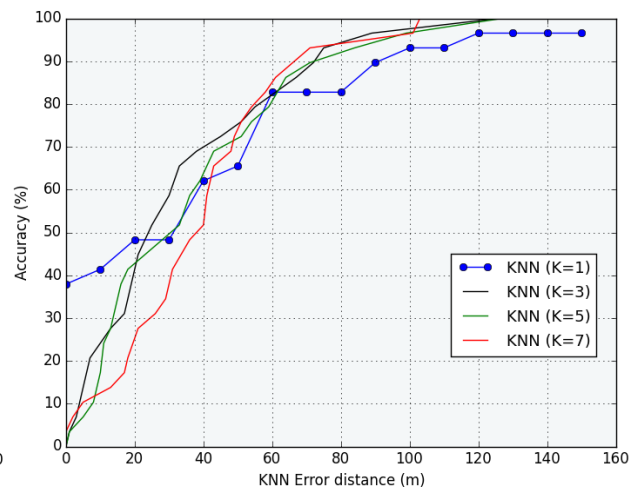
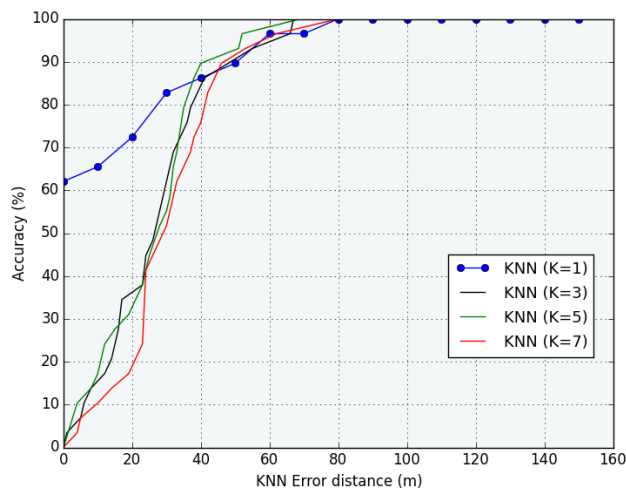
W-KNN EXPERIMENTAL RESULTS

```
In: nl.average_accuracy()
Out:
```

	Radio-MAP	Fingerprints	Mobiles	Stat Func	Avg. Accuracy	[PLOT]
1.	(None,	[None],	[1, 2],	'mean',	75.000000000),	
2.	(None,	[None],	[1, 2],	'median',	74.568965517),	
3.	(None,	[None],	[None],	'mean',	87.643678160),	A
4.	(None,	[None],	[None],	'median',	87.643678160),	
5.	(None,	[1],	[1, 2],	'mean',	67.959770114),	
6.	(None,	[1],	[1, 2],	'median',	66.810344827),	
7.	(None,	[1],	[None],	'mean',	68.965517241),	B
8.	(None,	[1],	[None],	'median',	69.540229885),	
9.	(None,	[2],	[1, 2],	'mean',	59.770114942),	
10.	(None,	[2],	[1, 2],	'median',	60.775862068),	
11.	(None,	[2],	[None],	'mean',	60.632183908),	C
12.	(None,	[2],	[None],	'median',	58.333333333),	
13.	(None,	[1, 2],	[1, 2],	'mean',	63.864942528),	
14.	(None,	[1, 2],	[1, 2],	'median',	63.793103448),	
15.	(None,	[1, 2],	[None],	'mean',	64.798850574),	
16.	(None,	[1, 2],	[None],	'median',	63.936781609),	
17.	(1,	[None],	[1, 2],	'mean',	57.327586206),	
18.	(1,	[None],	[1, 2],	'median',	59.195402298),	
19.	(1,	[None],	[None],	'mean',	60.632183908),	D
20.	(1,	[None],	[None],	'median',	59.482758620),	
21.	(1,	[1],	[1, 2],	'mean',	74.712643678),	
22.	(1,	[1],	[1, 2],	'median',	77.729885057),	
23.	(1,	[1],	[None],	'mean',	89.367816091),	E
24.	(1,	[1],	[None],	'median',	91.091954022),	
25.	(1,	[2],	[1, 2],	'mean',	54.454022988),	
26.	(1,	[2],	[1, 2],	'median',	53.591954022),	
27.	(1,	[2],	[None],	'mean',	49.425287356),	F
28.	(1,	[2],	[None],	'median',	48.563218390),	
29.	(1,	[1, 2],	[1, 2],	'mean',	64.583333333),	
30.	(1,	[1, 2],	[1, 2],	'median',	65.660919540),	
31.	(1,	[1, 2],	[None],	'mean',	69.396551724),	
32.	(1,	[1, 2],	[None],	'median',	69.827586206)]	

NOTE: "None" is used to represent fingerprint or mobile merging.

Selecting only those whose statistical function is the mean and using merged mobiles, we end up with 8 accuracy plots, from where we can exclude those whose fingerprints are considered independently, i.e. [1,2]. The accuracy plots are shown next.



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ROUND-TRIP METHOD IMPLEMENTATION IN GNU-RADIO COMPANION

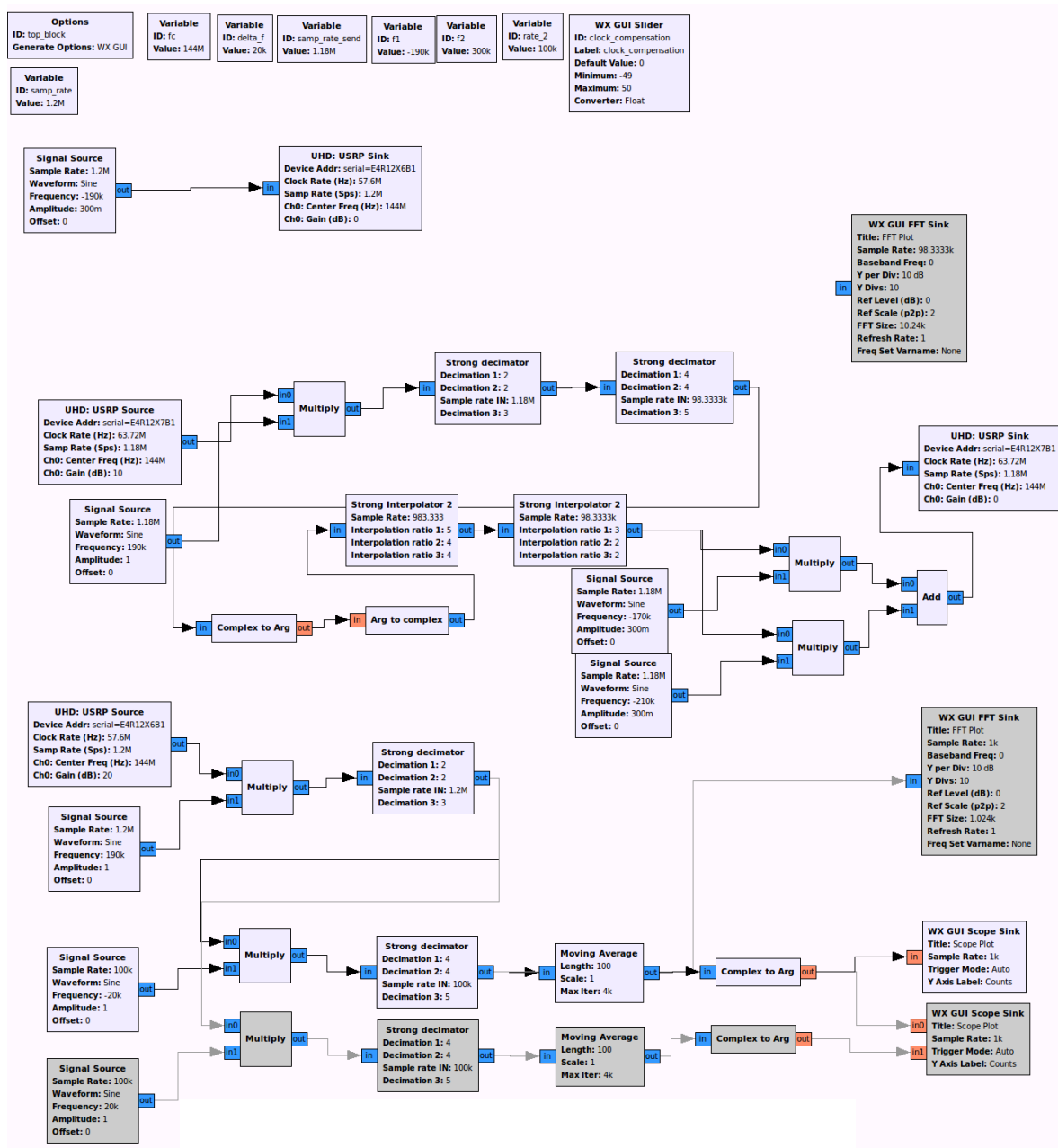


Figure 61 – Implementation of the round-trip method

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